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Higuchi et al.

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(54) **NONVOLATILE SEMICONDUCTOR
MEMORY DEVICE INCLUDING A CHARGE
STORAGE LAYER FORMED ON FIRST AND
SECOND INSULATING LAYERS**

USPC 257/324
See application file for complete search history.

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H01L 29/792 (2006.01)
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CPC **H01L 29/792** (2013.01); **H01L 21/28282**
(2013.01); **H01L 29/4234** (2013.01); **H01L**
29/513 (2013.01); **H01L 29/66833** (2013.01)

(58) **Field of Classification Search**
CPC H01L 21/28282; H01L 29/4234;
H01L 29/66833

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Primary Examiner — Howard Weiss

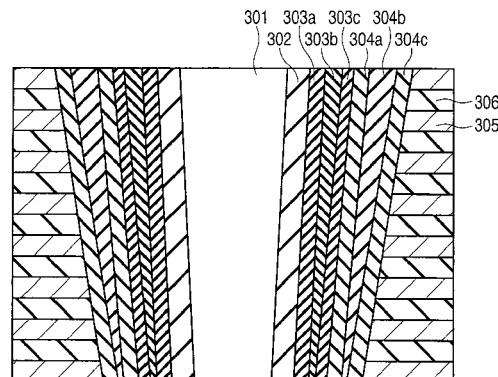
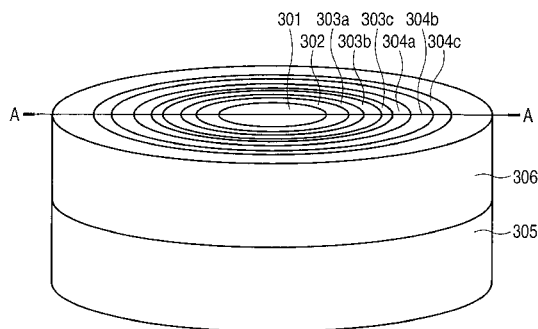
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(57) **ABSTRACT**

According to one embodiment, a nonvolatile semiconductor
memory device including a semiconductor layer with a main
surface, a first insulating layer formed on the main surface of
the semiconductor layer, a charge storage layer formed on the
first insulating layer, a second insulating layer formed on the
charge storage layer, and a control gate electrode formed on
the second insulating layer. At least one inelastic scattering
film that reduces energy of electrons by scattering is con-
tained in at least one of the charge storage layer and second
insulating layer.

12 Claims, 22 Drawing Sheets



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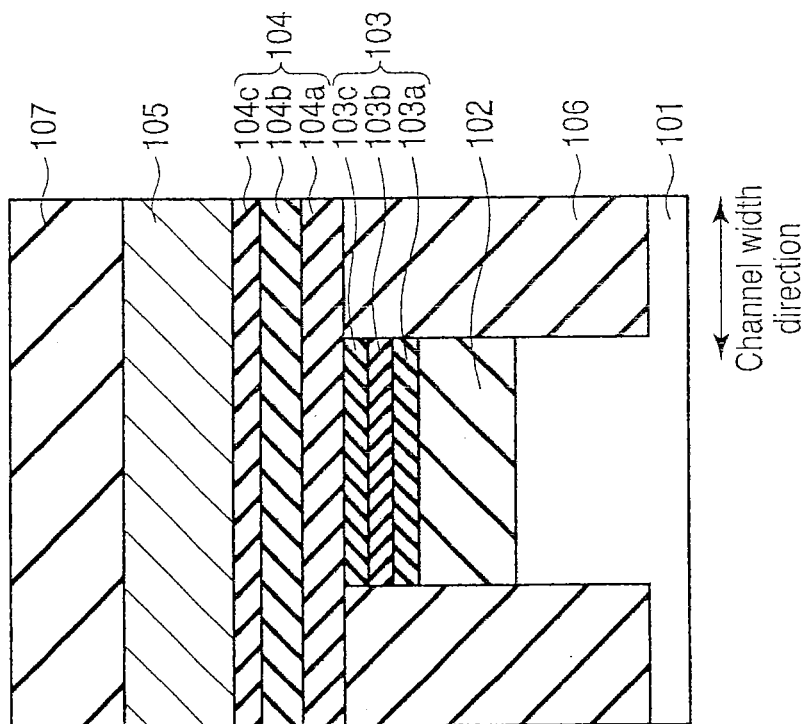


FIG. 1A

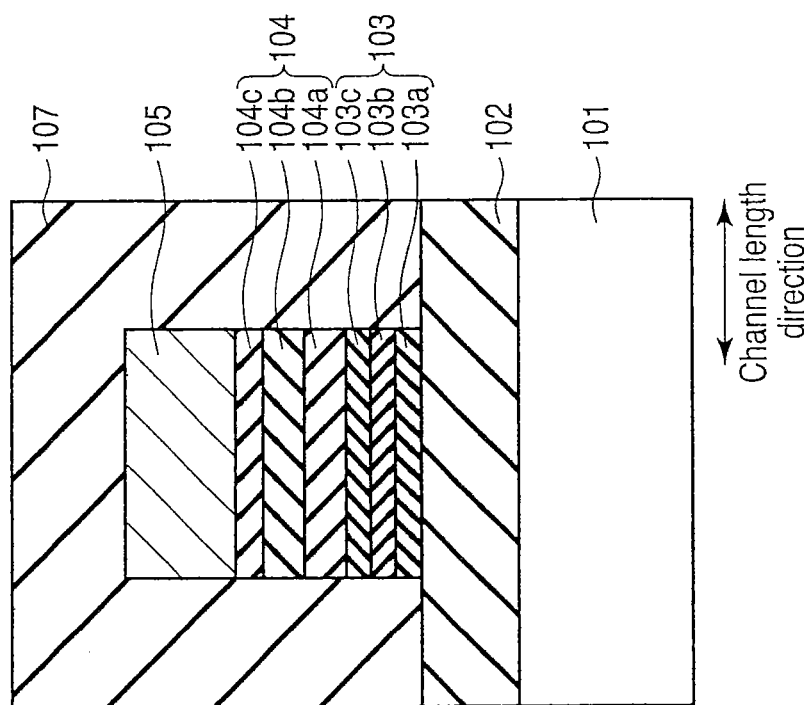


FIG. 1B

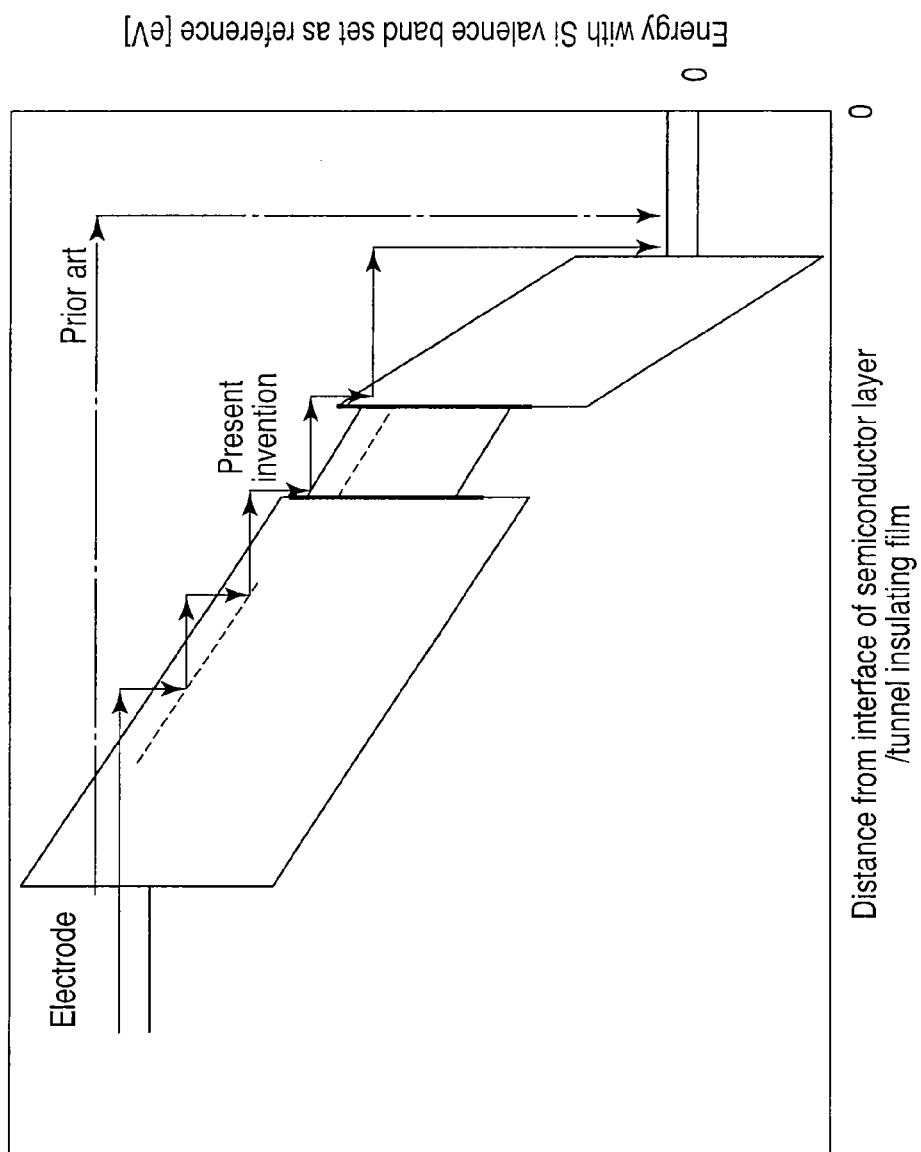


FIG. 2

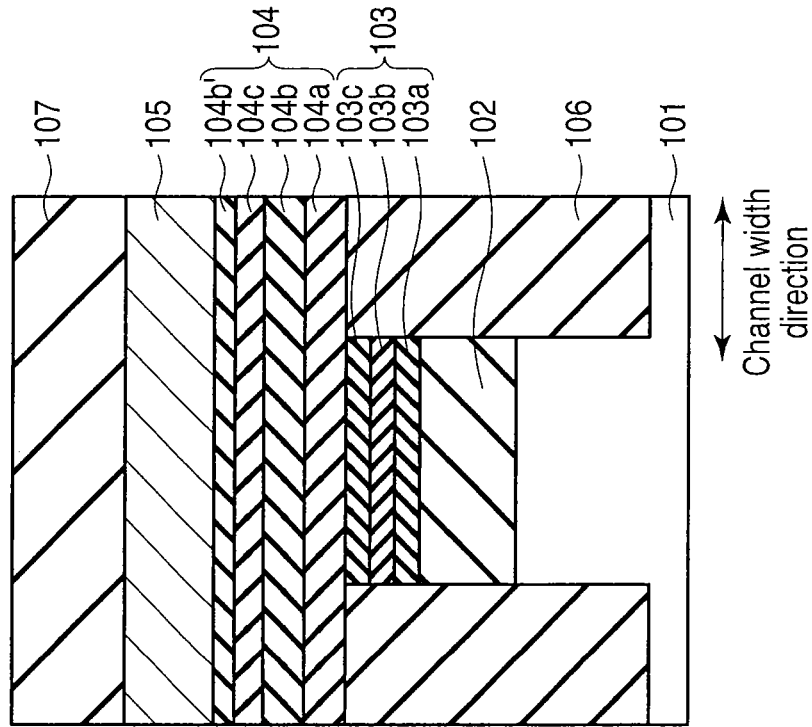


FIG. 3B

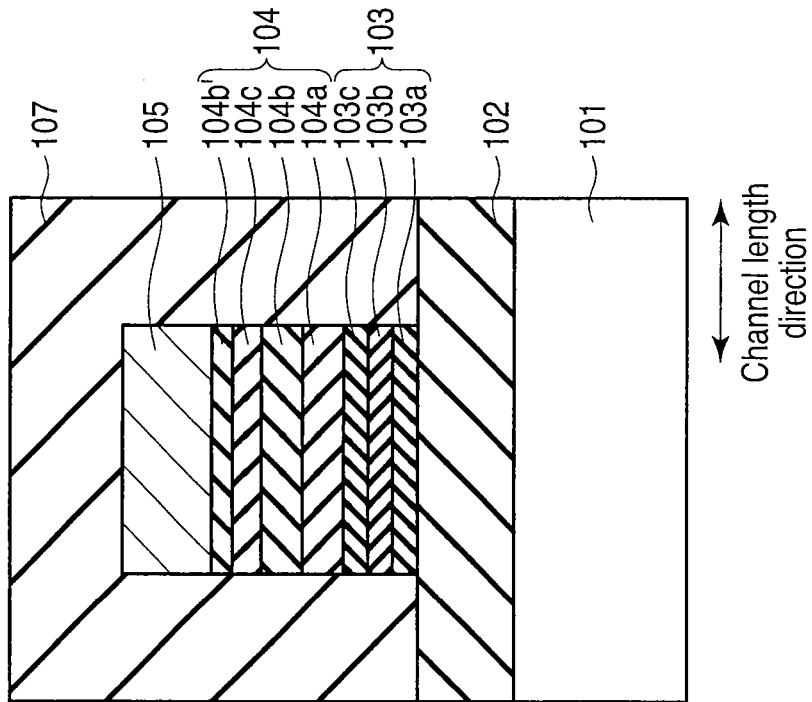


FIG. 3A

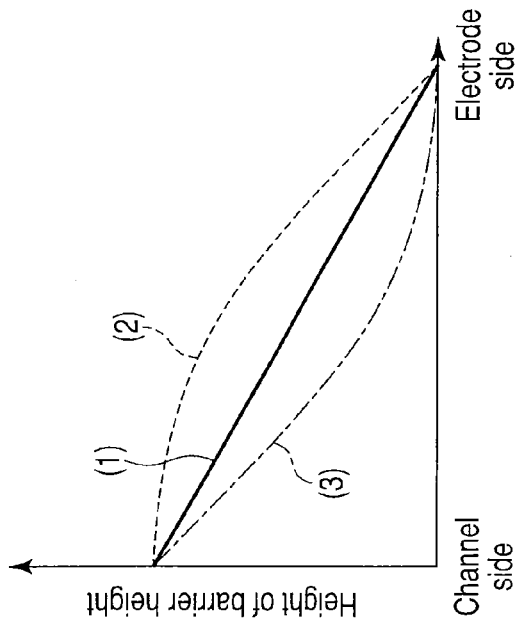


FIG. 4B

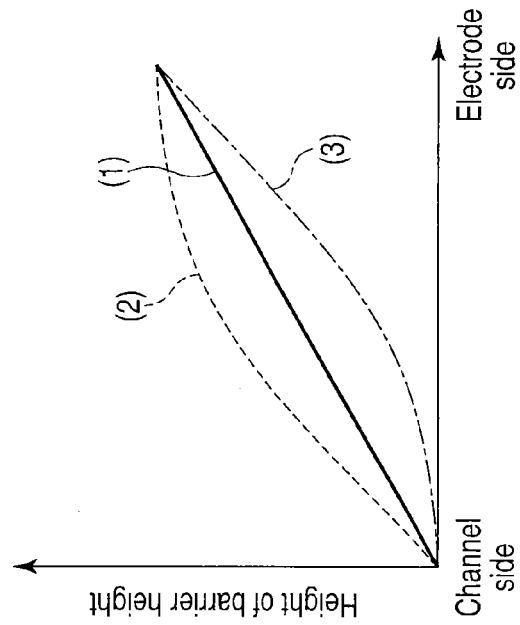


FIG. 4C

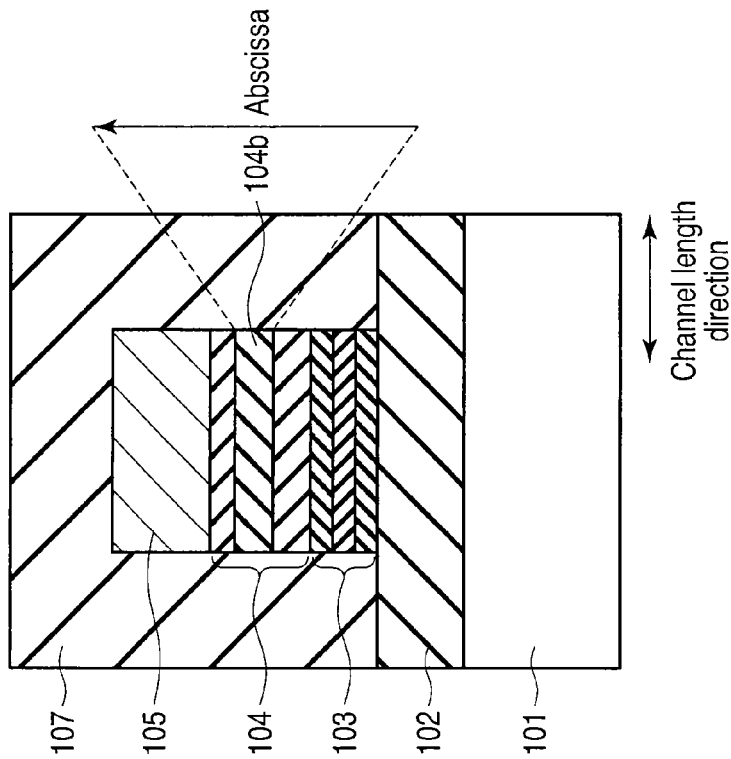


FIG. 4A

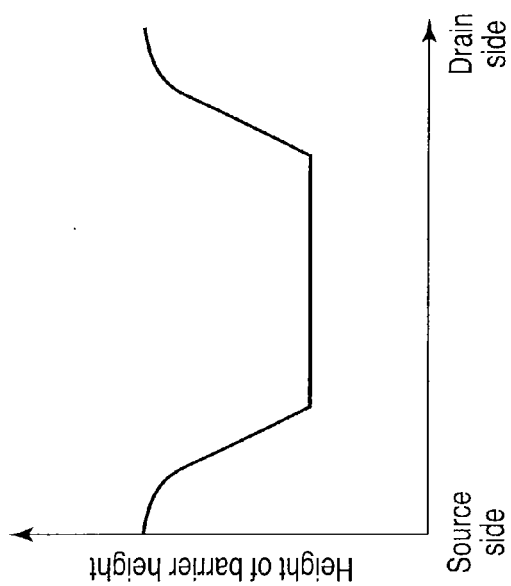


FIG. 5B

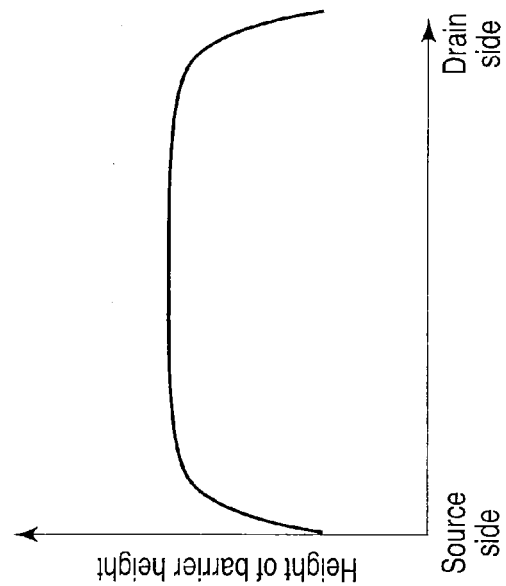


FIG. 5C

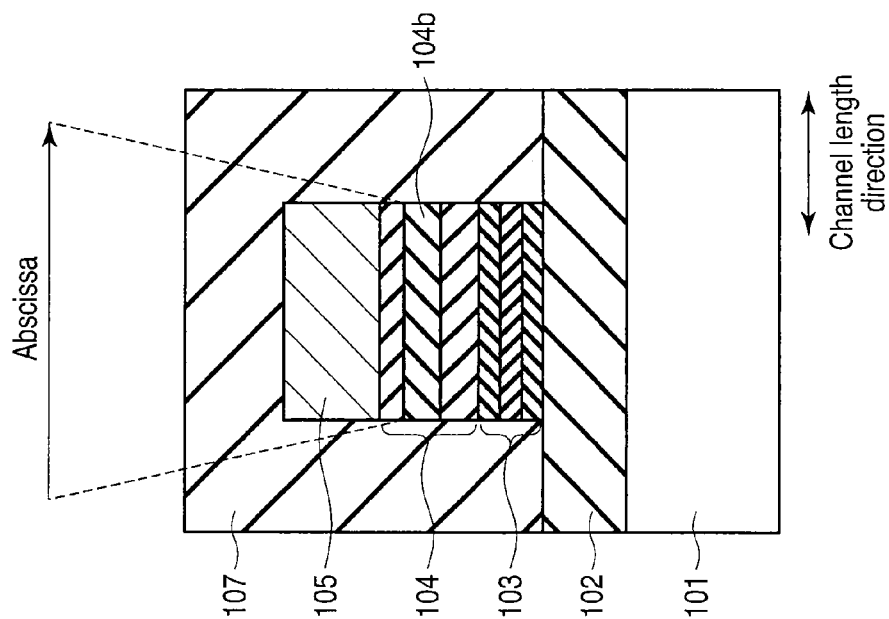


FIG. 5A

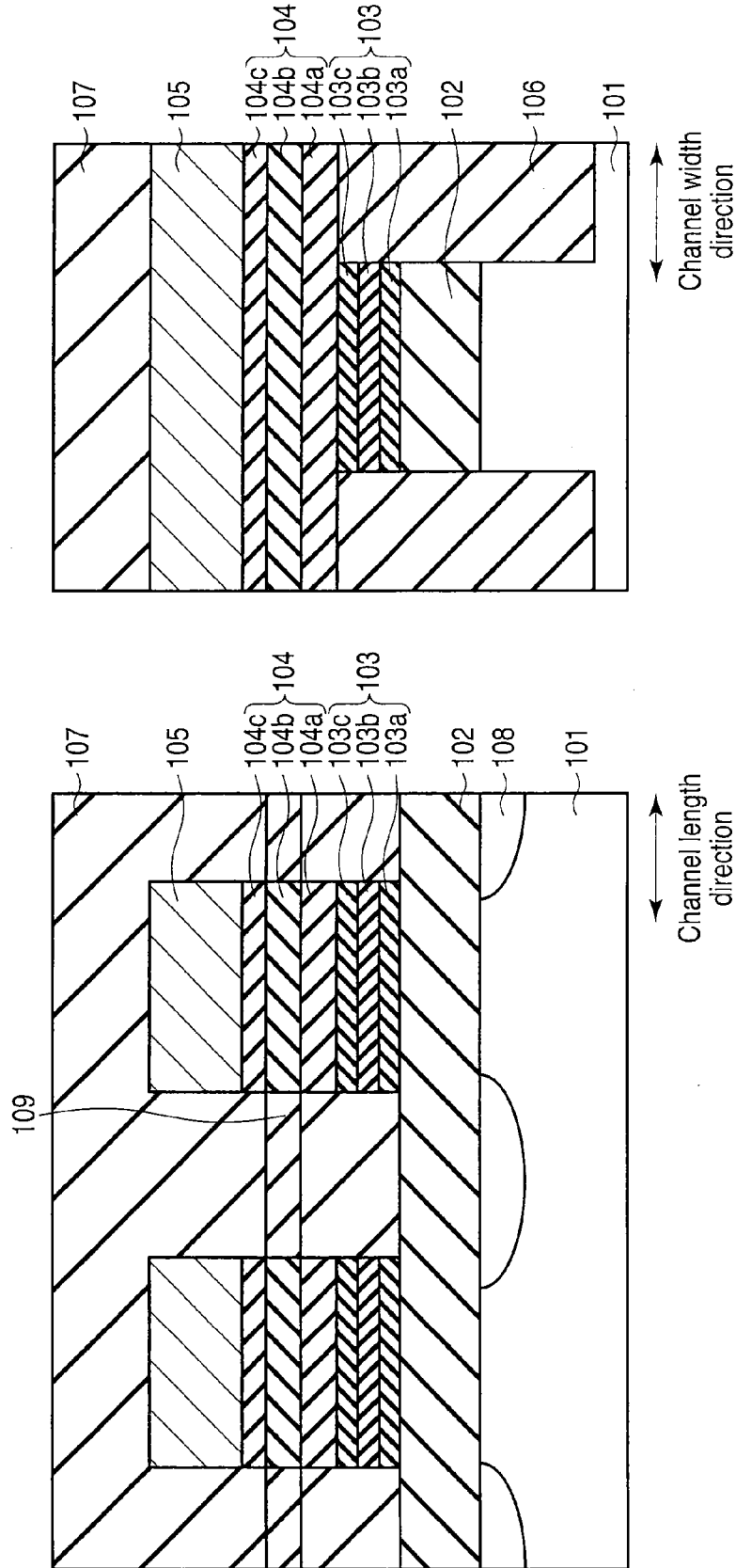


FIG. 6B

FIG. 6A

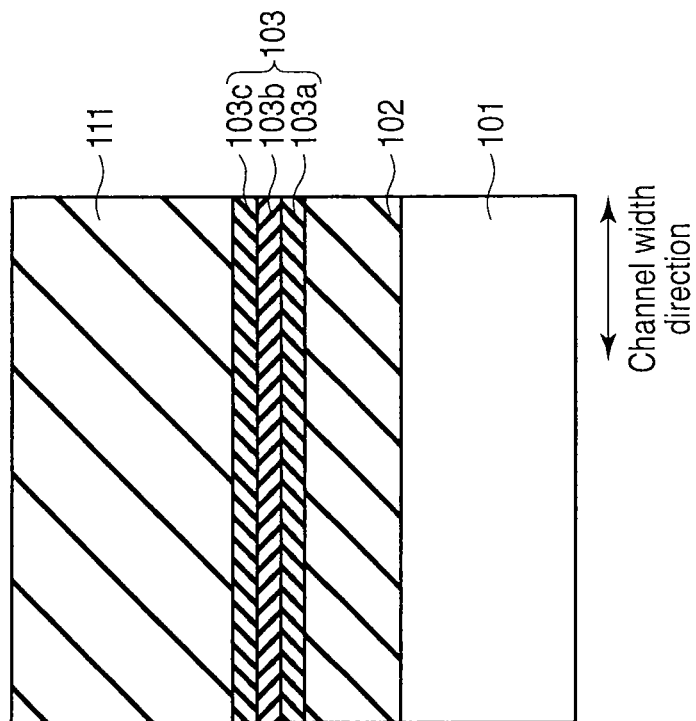


FIG. 7B

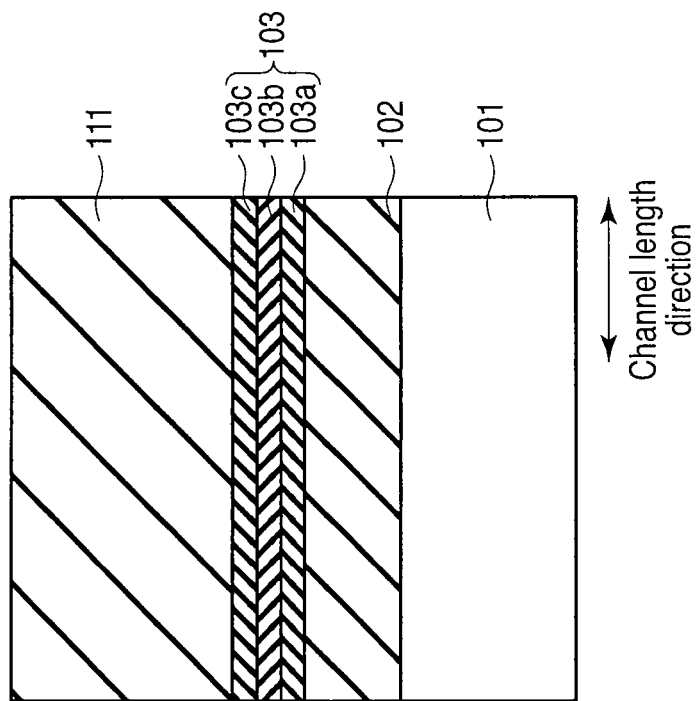


FIG. 7A

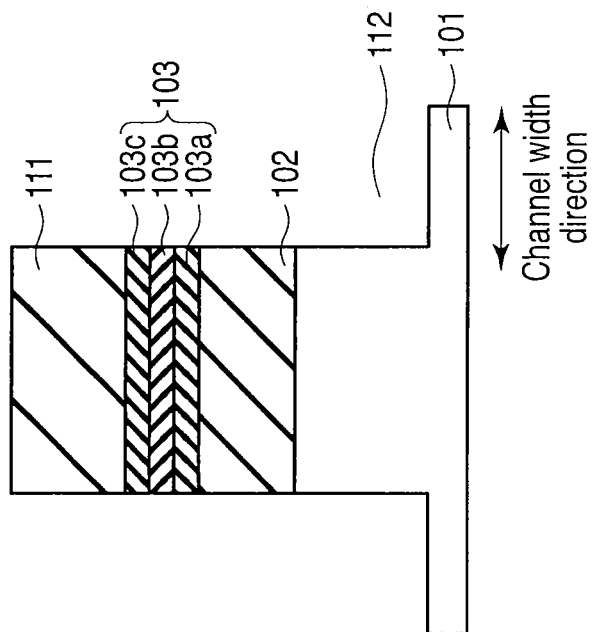


FIG. 8A

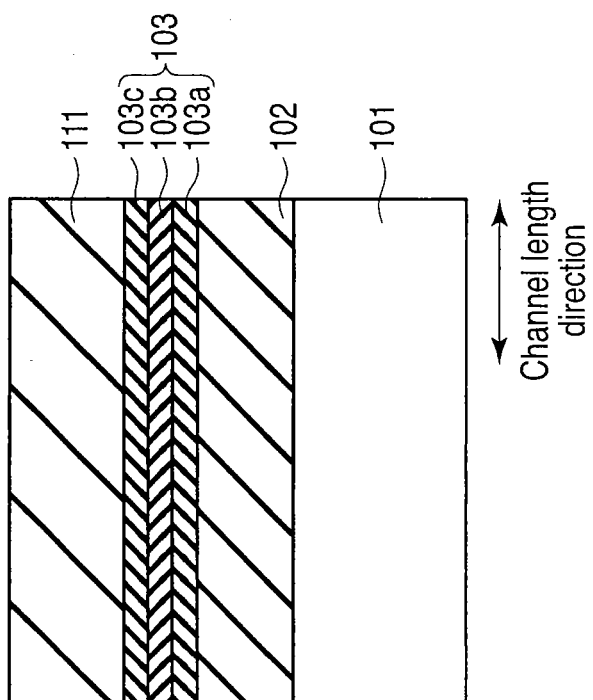


FIG. 8B

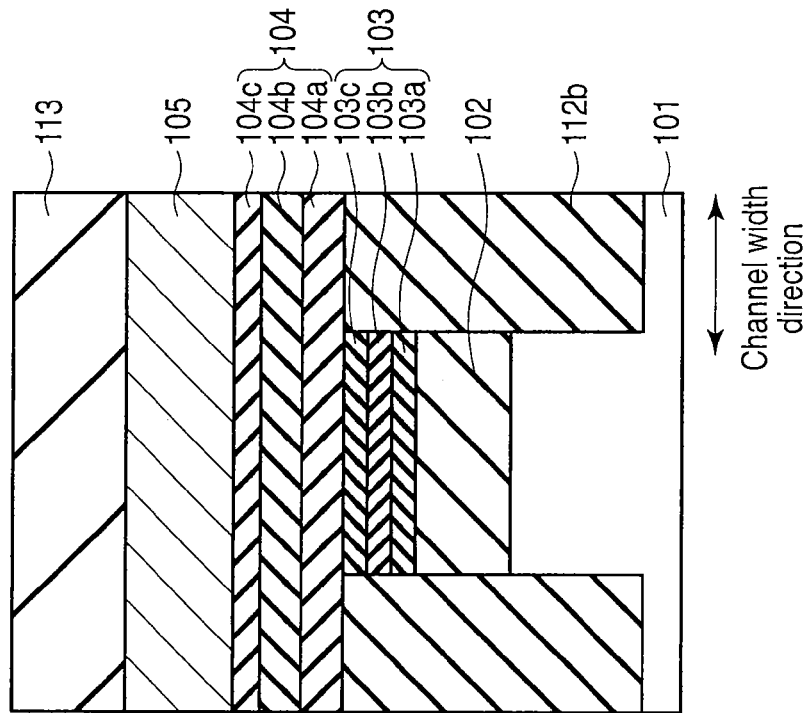


FIG. 9B

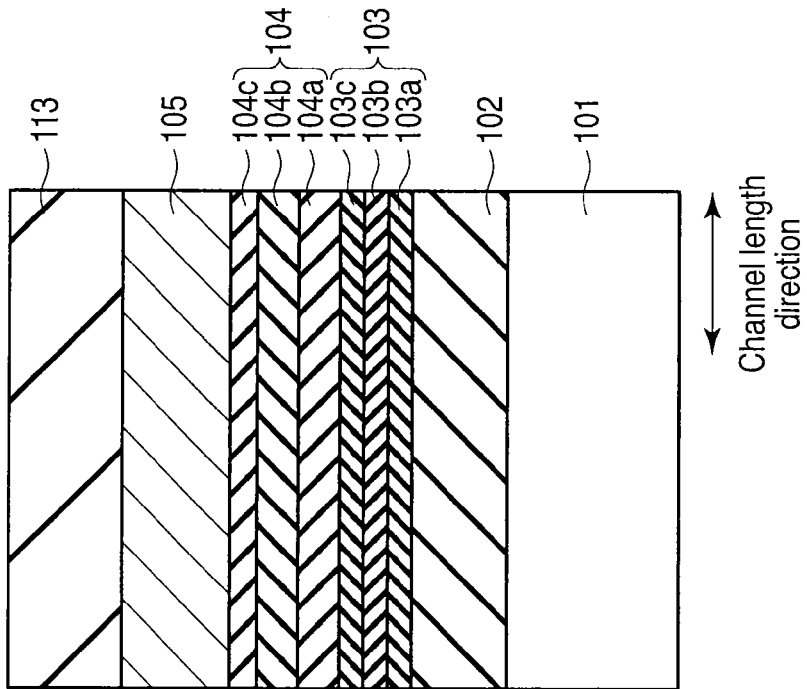


FIG. 9A

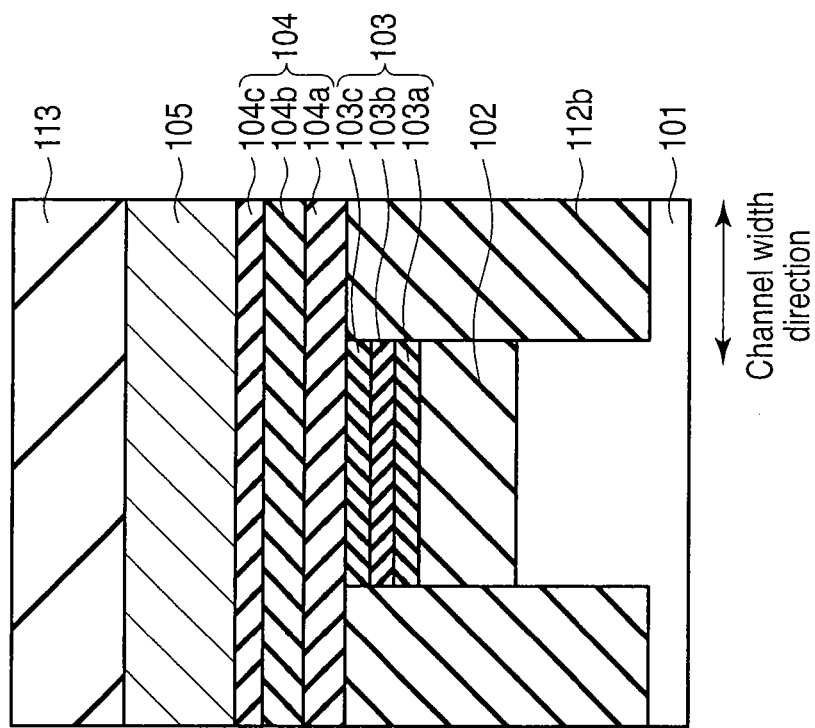


FIG. 10B

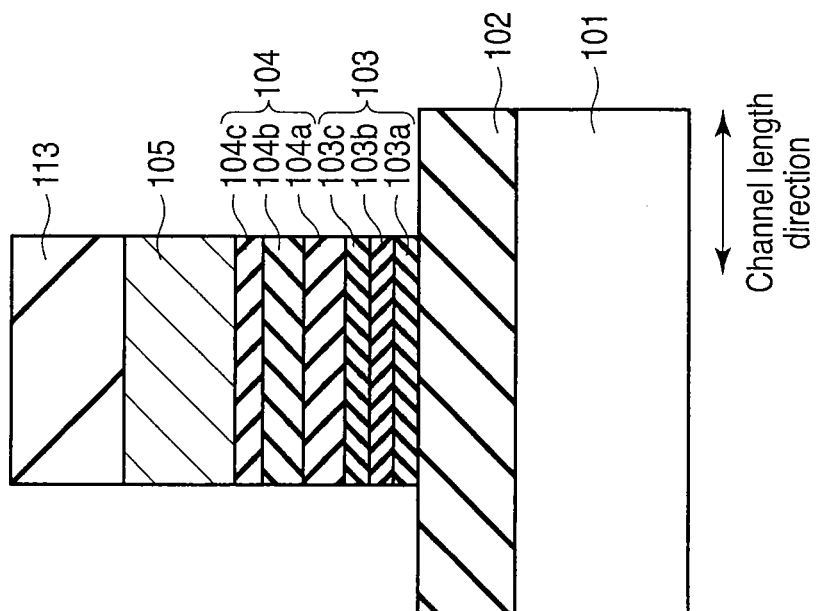


FIG. 10A

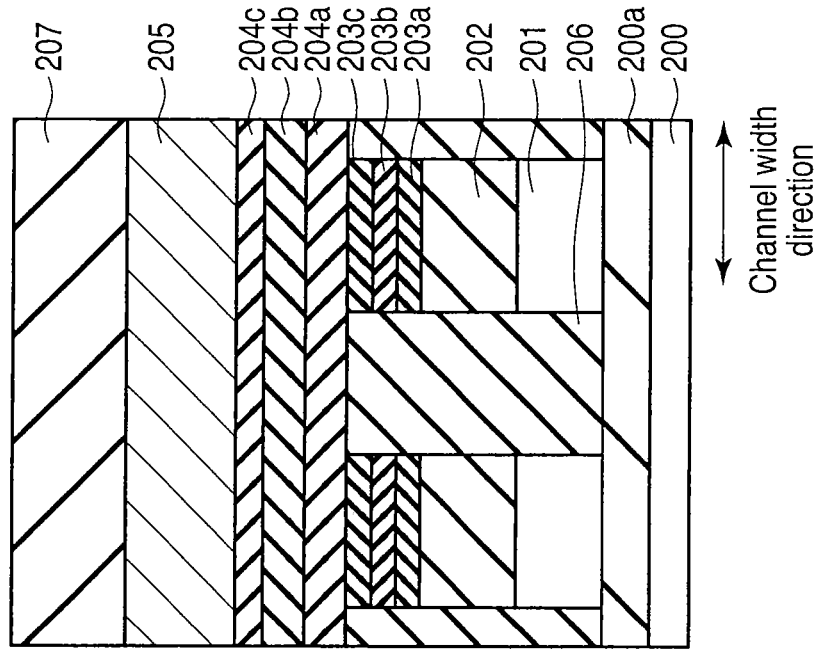


FIG. 11A

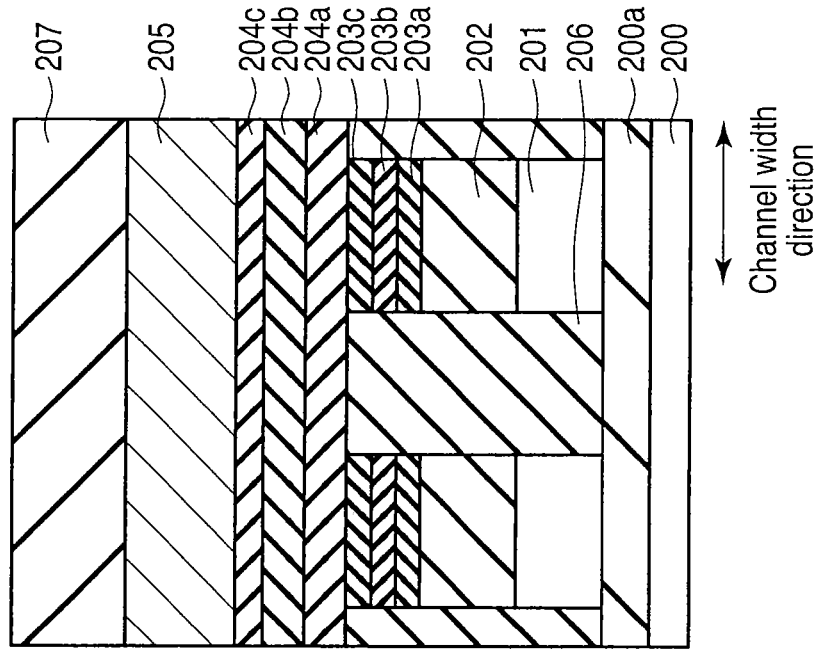


FIG. 11B

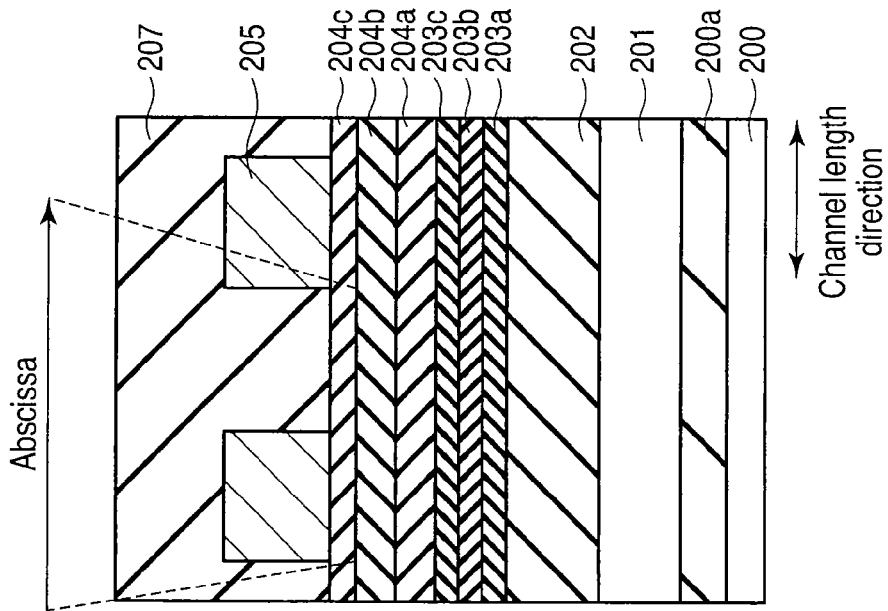


FIG. 12A

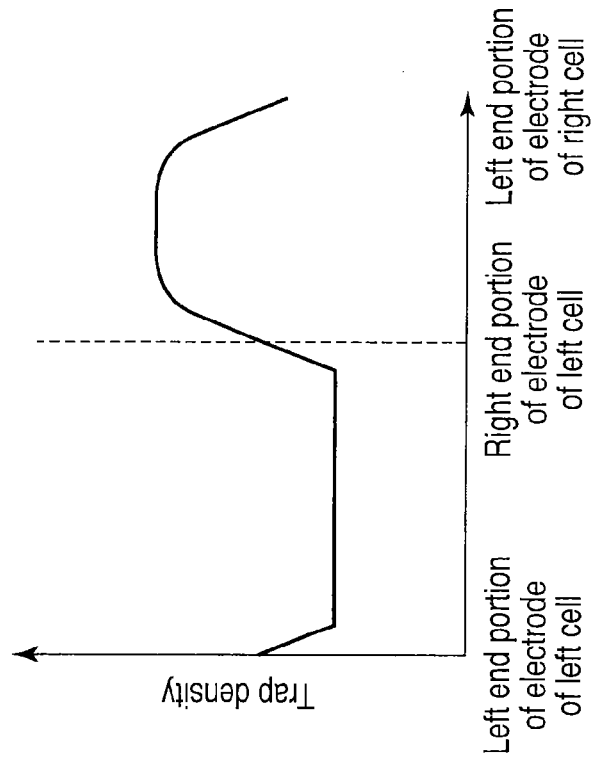


FIG. 12B

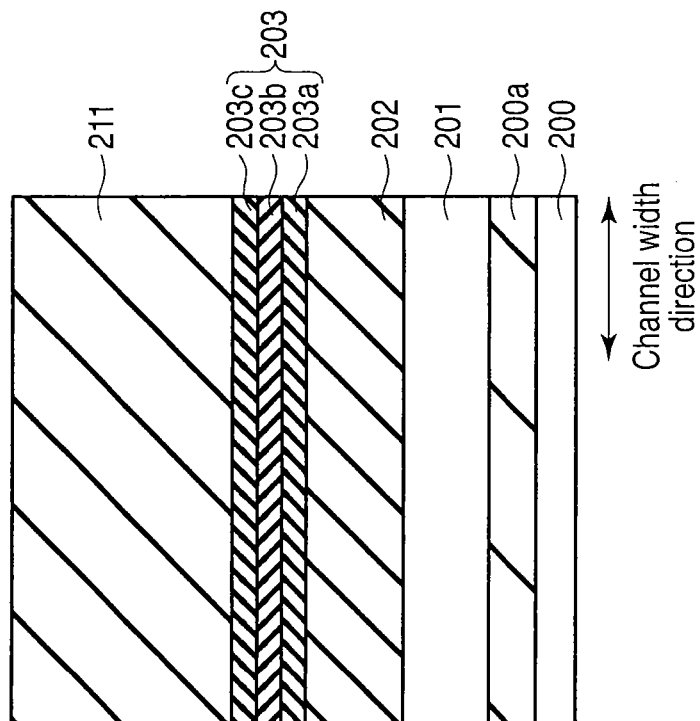


FIG. 13A

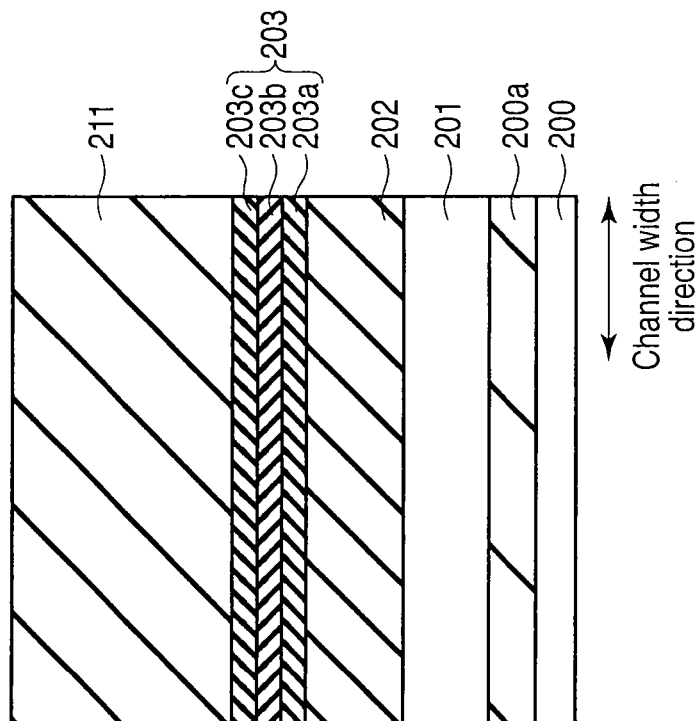


FIG. 13B

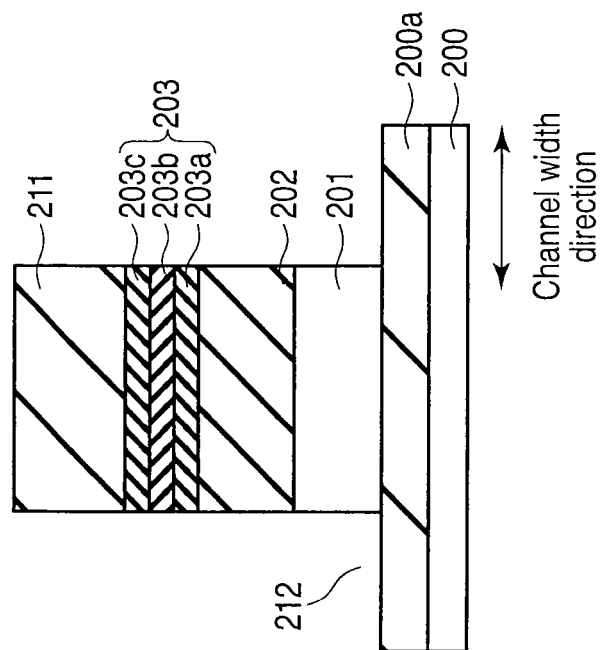


FIG. 14B

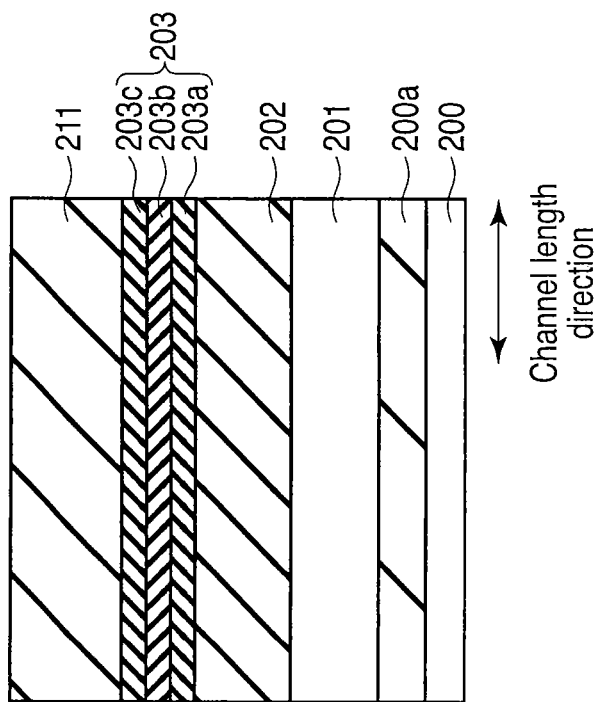


FIG. 14A

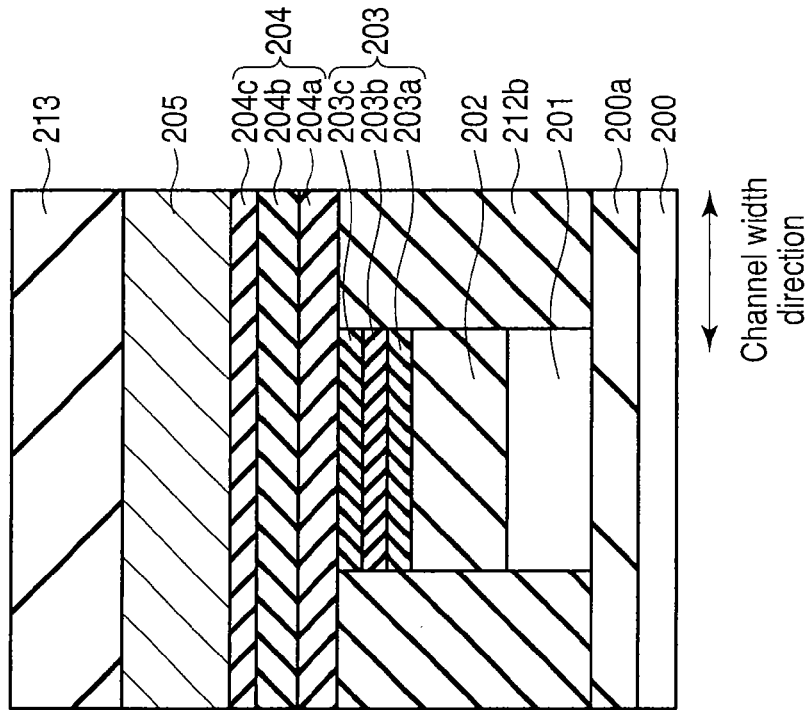


FIG. 15A

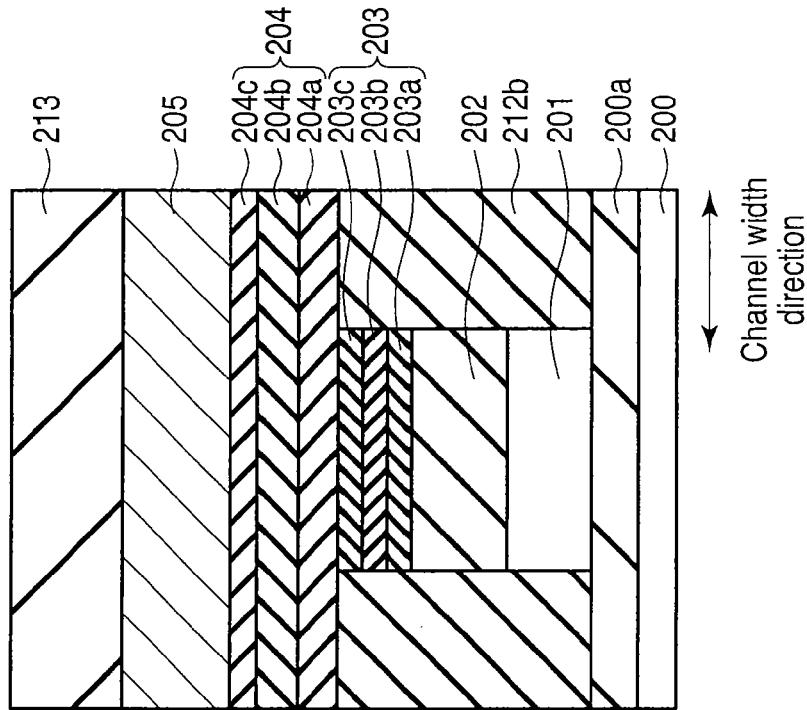


FIG. 15B

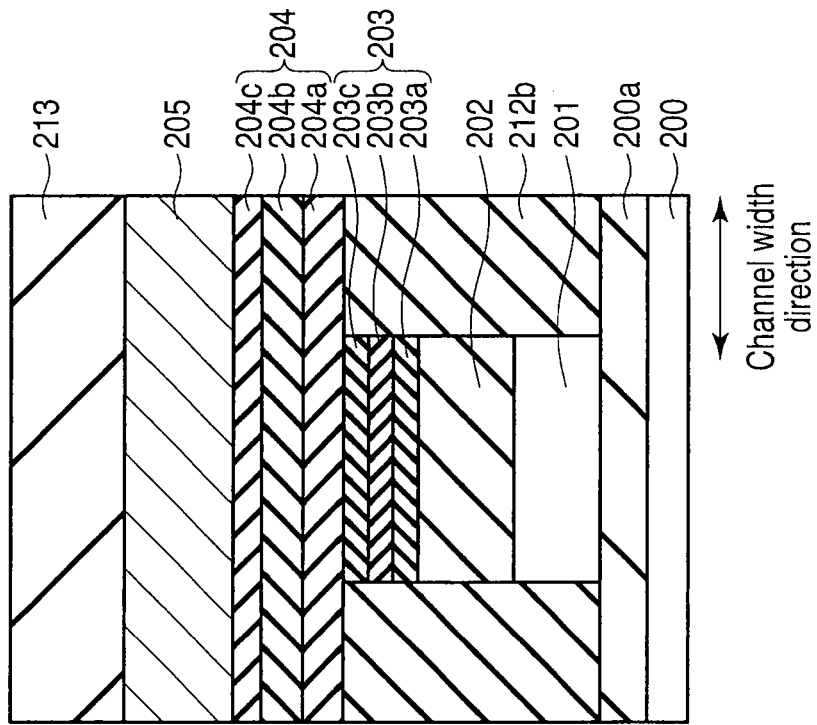


FIG. 16B

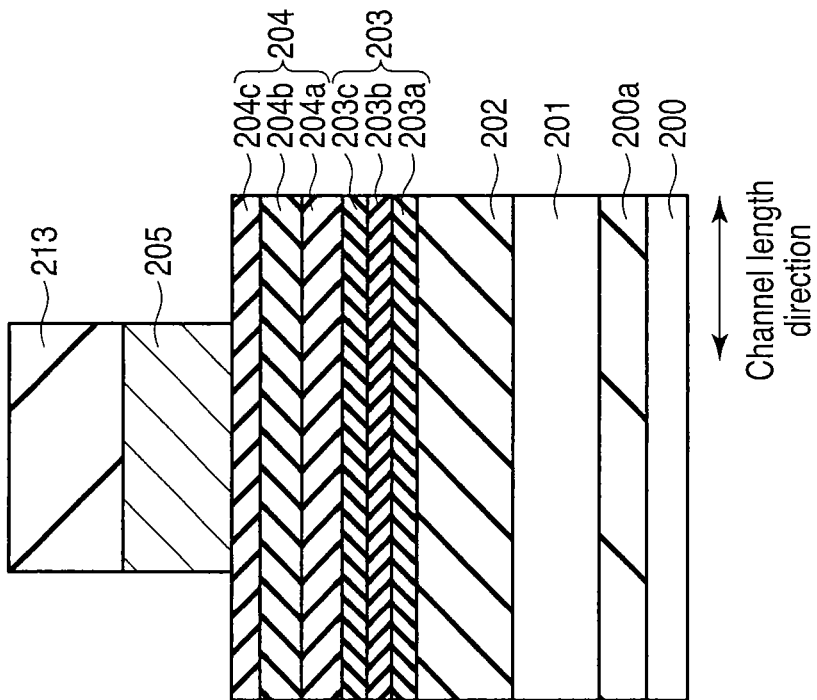


FIG. 16A

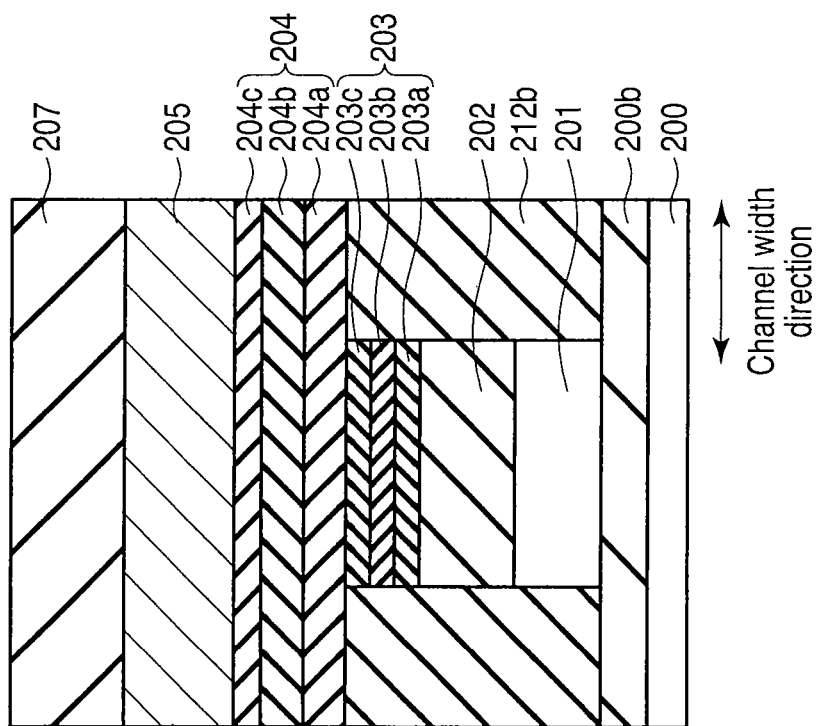


FIG. 17A

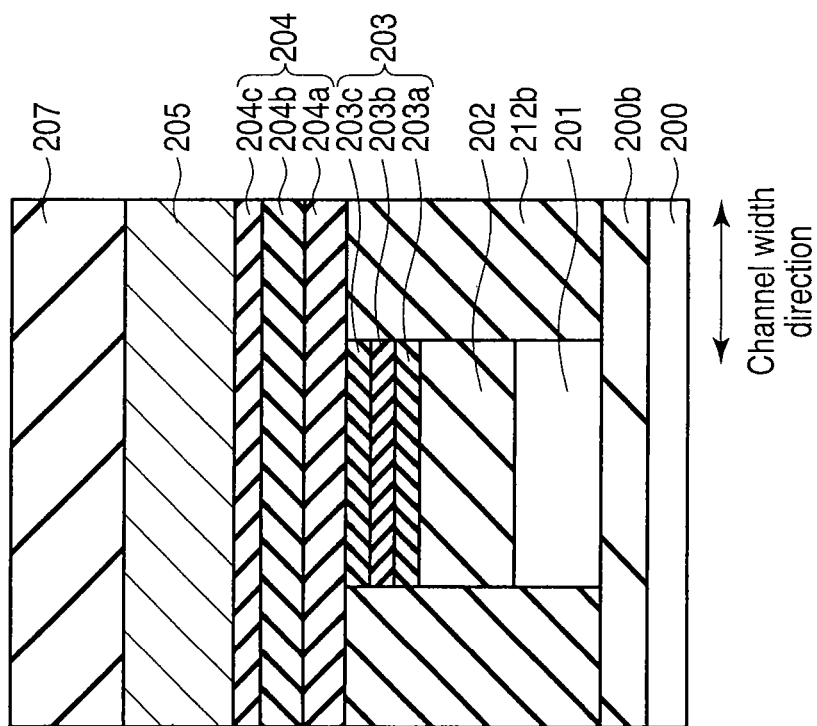


FIG. 17B

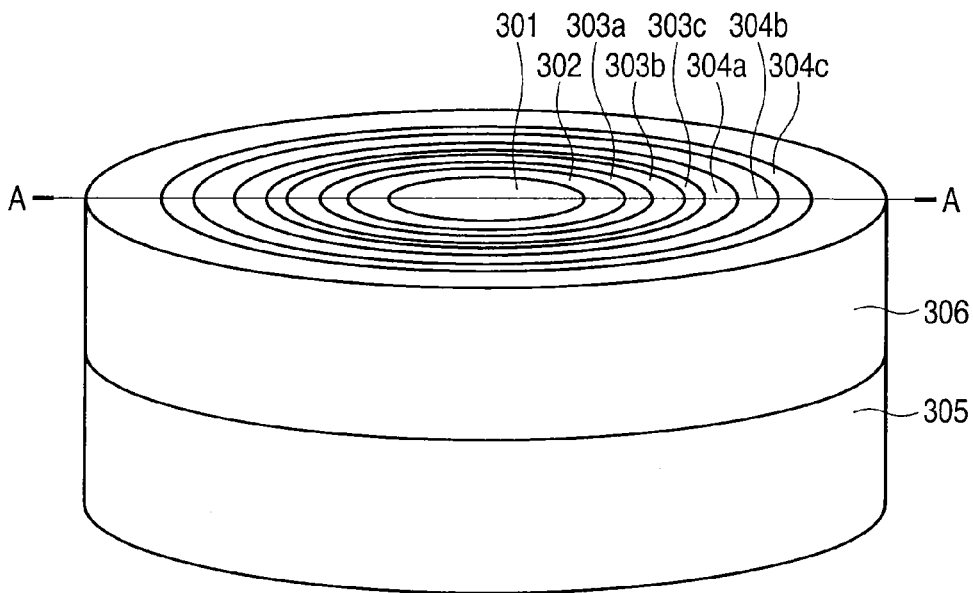


FIG. 18A

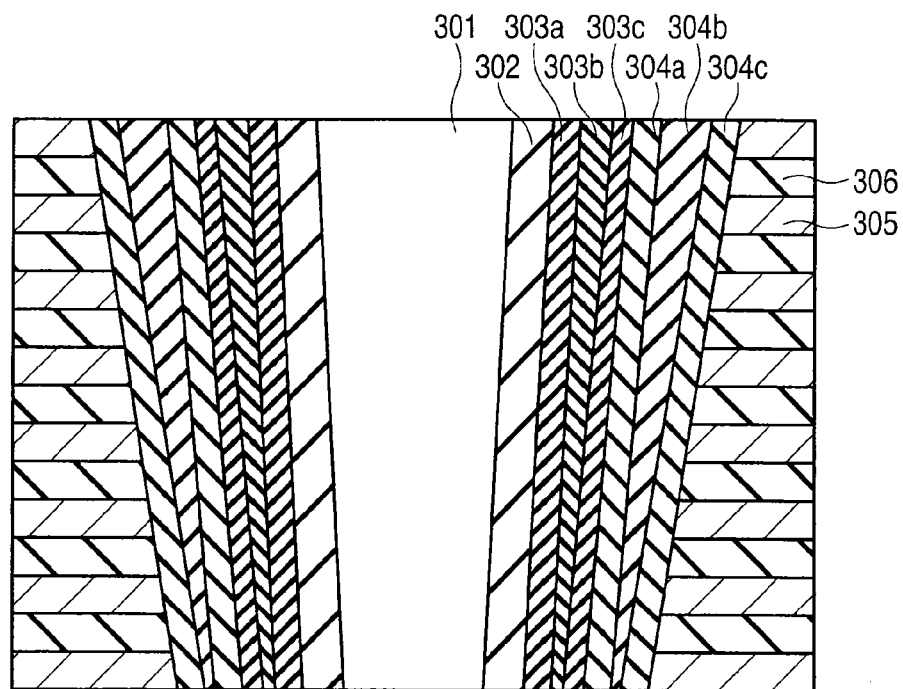


FIG. 18B

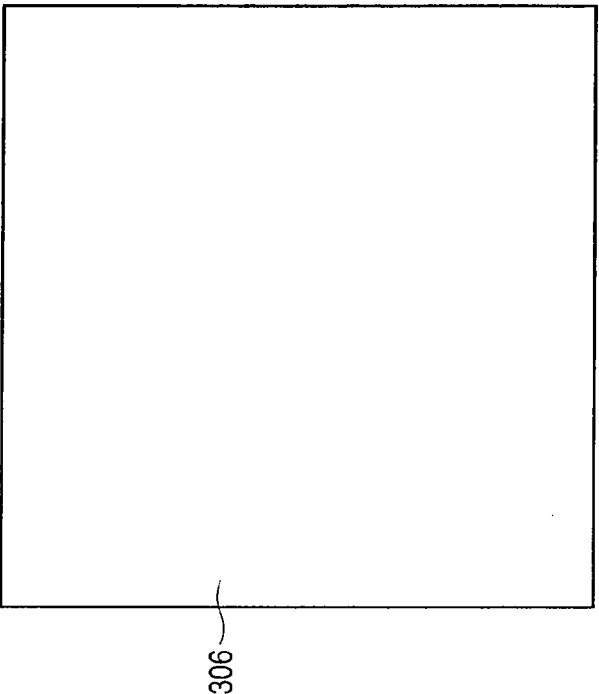


FIG. 19B

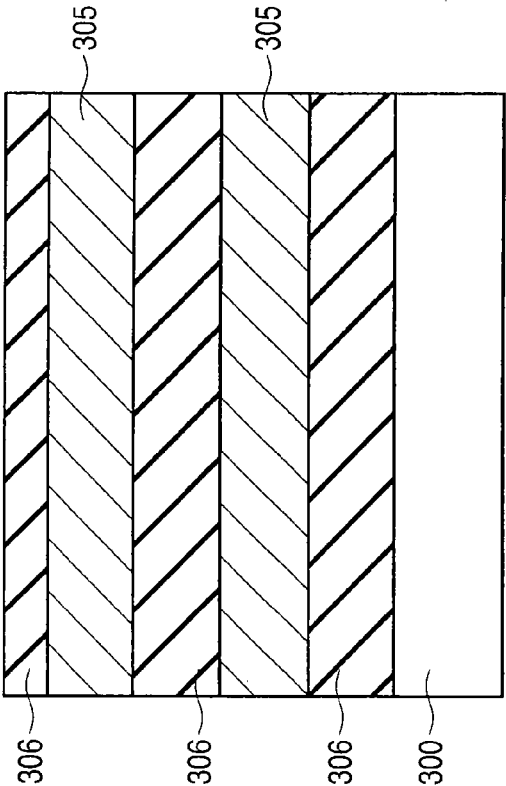


FIG. 19A

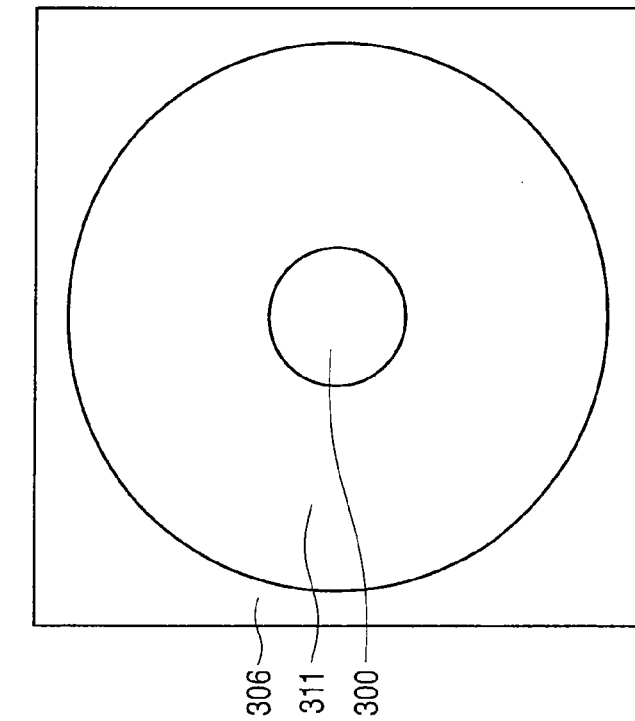


FIG. 20B

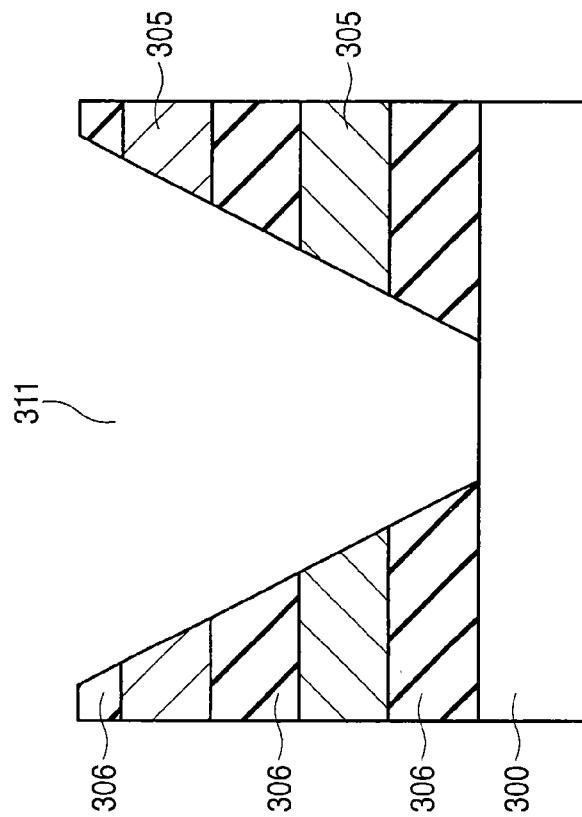


FIG. 20A

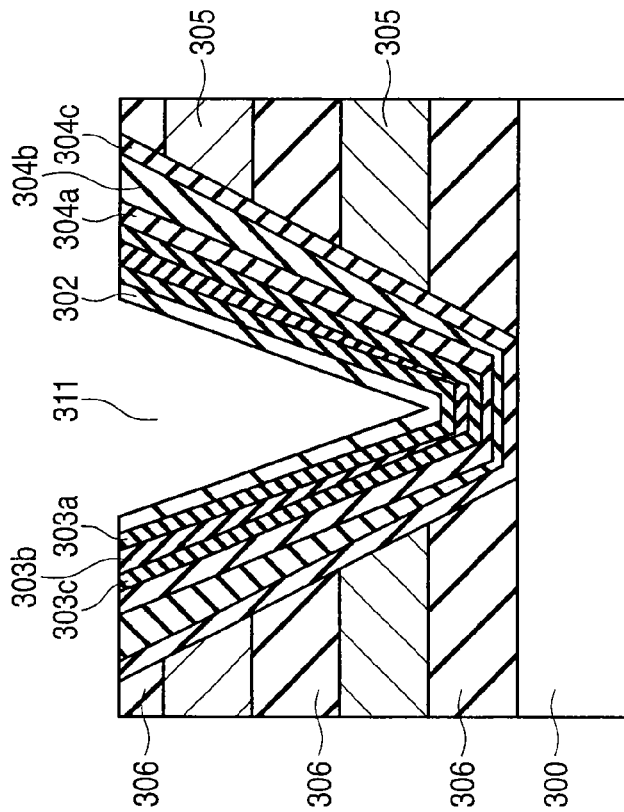


FIG. 21A

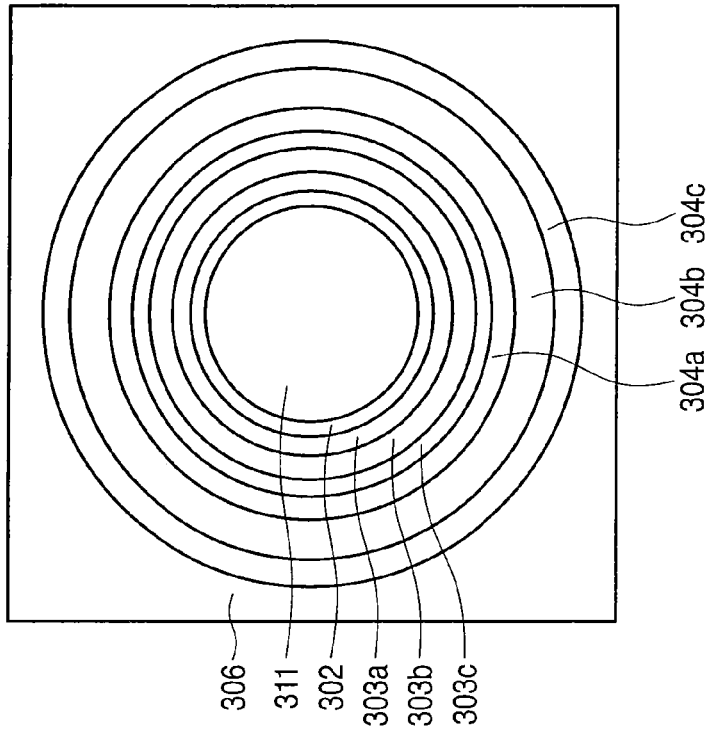


FIG. 21B

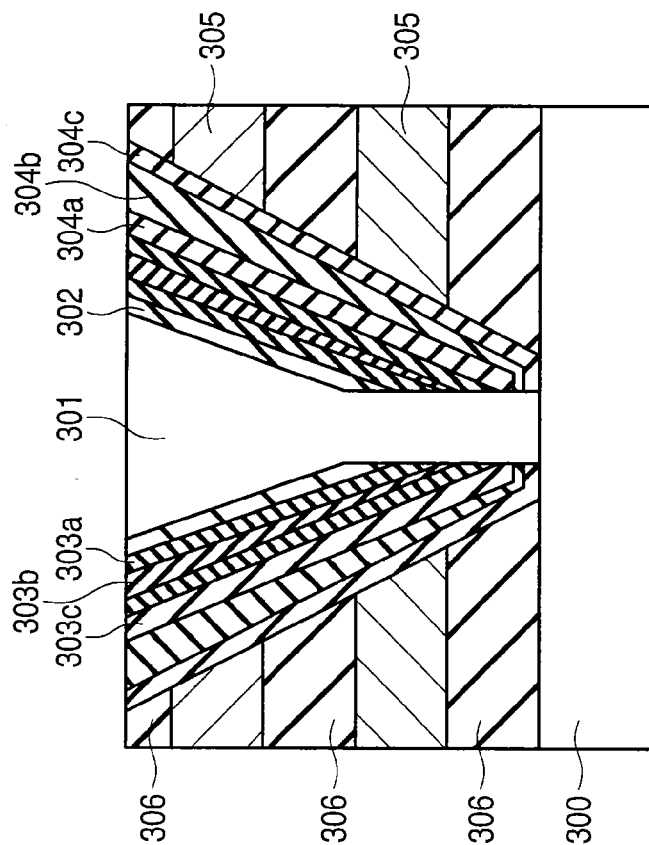


FIG. 22A

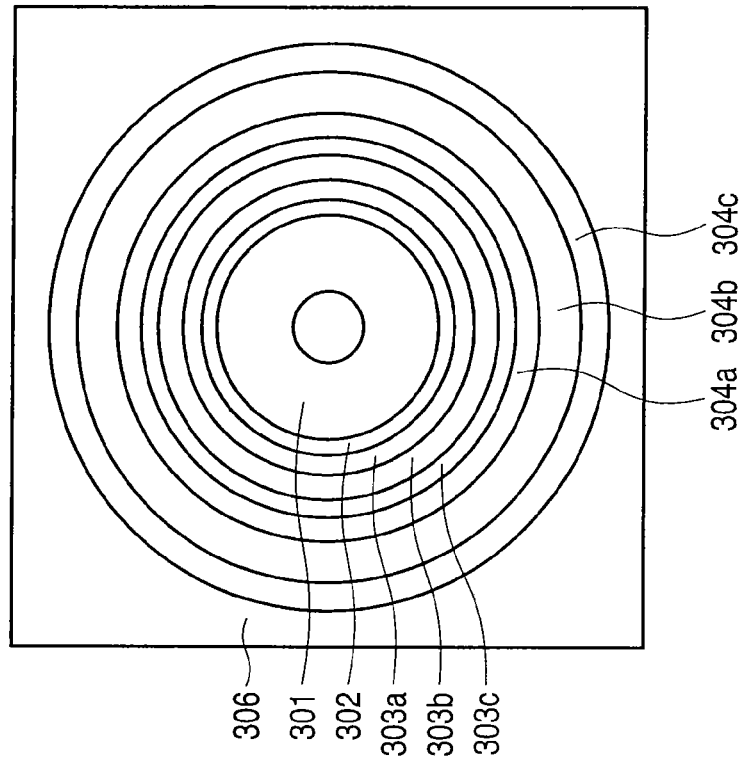


FIG. 22B

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NONVOLATILE SEMICONDUCTOR MEMORY DEVICE INCLUDING A CHARGE STORAGE LAYER FORMED ON FIRST AND SECOND INSULATING LAYERS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon and claims the benefit of priority from Japanese Patent Application No. 2009-194542, filed Aug. 25, 2009; the entire contents of which are incorporated herein by reference.

FIELD

Embodiments described herein relate generally to a non-volatile semiconductor memory device and a manufacturing method thereof.

BACKGROUND

As one example of the structure of a memory cell in a nonvolatile semiconductor memory device, a metal/oxide film/nitride film/oxide film/semiconductor (MONOS) structure in which interference between adjacent memory cells is suppressed is provided (for example, see Jp-A 2009-16615 (KOKAI)).

The MONOS memory cell is defined as a memory cell in which a charge storage layer is formed of an insulating body having a charge trap function. Therefore, a structure in which the charge storage layer is formed above the upper surface of a semiconductor layer with a tunnel insulating film disposed therebetween and a control gate electrode is formed above the upper surface of the charge storage layer with a charge block layer disposed therebetween is provided.

At the erase operation time of the MONOS memory cell, the semiconductor layer is grounded and a negative voltage is applied to the control gate electrode. By setting the above voltage relation, holes are injected from the semiconductor layer into the charge storage layer. Therefore, electrons stored in the charge storage layer will disappear.

In the memory cell, insulation of the charge block layer is not complete. Therefore, electrons will leak from the control gate electrode towards the semiconductor layer at the erase operation time. Electrons having leaked from the control gate electrode are accelerated until they reach the interface of the tunnel insulating film/semiconductor layer and gain a great amount of energy. Thus, the electrons are impact-ionized in the semiconductor layer. Therefore, damage is done to the tunnel insulating film and the interface of the tunnel insulating film/semiconductor layer and insulation of the tunnel insulating film is degraded. As a result, there occurs a problem that the charge holding characteristic of the memory cell will be degraded.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A and 1B are cross-sectional views showing the structure of a MONOS memory cell according to a first embodiment.

FIG. 2 is a band diagram in the first embodiment.

FIGS. 3A and 3B are cross-sectional views showing the structure of the MONOS memory cell according to the first embodiment.

FIGS. 4A, 4B and 4C are a cross-sectional view and diagrams for illustrating the structure of a MONOS memory cell according to a modification of the first embodiment.

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FIGS. 5A, 5B and 5C are a cross-sectional view and diagrams for illustrating the structure of a MONOS memory cell according to a modification of the first embodiment.

FIGS. 6A and 6B are cross-sectional views showing the structure of a MONOS memory cell according to a modification of the first embodiment.

FIGS. 7A and 7B are cross-sectional views showing a manufacturing step of the MONOS memory cell according to the first embodiment.

FIGS. 8A and 8B are cross-sectional views showing a manufacturing step of the MONOS memory cell according to the first embodiment.

FIGS. 9A and 9B are cross-sectional views showing a manufacturing step of the MONOS memory cell according to the first embodiment.

FIGS. 10A and 10B are cross-sectional views showing a manufacturing step of the MONOS memory cell according to the first embodiment.

FIGS. 11A and 11B are cross-sectional views showing the structure of a depletion MONOS memory cell according to a second embodiment.

FIGS. 12A and 12B are a cross-sectional view and diagram respectively showing the structure of and trap density in a depletion MONOS memory cell according to a modification of the second embodiment.

FIGS. 13A and 13B are cross-sectional views showing a manufacturing step of the depletion MONOS memory cell according to the second embodiment.

FIGS. 14A and 14B are cross-sectional views showing a manufacturing step of the depletion MONOS memory cell according to the second embodiment.

FIGS. 15A and 15B are cross-sectional views showing a manufacturing step of the depletion MONOS memory cell according to the second embodiment.

FIGS. 16A and 16B are cross-sectional views showing a manufacturing step of the depletion MONOS memory cell according to the second embodiment.

FIGS. 17A and 17B are cross-sectional views showing a manufacturing step of the depletion MONOS memory cell according to the second embodiment.

FIGS. 18A and 18B are a bird's-eye view and cross-sectional view showing the structure of a BiCS memory according to a third embodiment.

FIGS. 19A and 19B are cross-sectional views showing a manufacturing step of the BiCS memory according to the third embodiment.

FIGS. 20A and 20B are cross-sectional views showing a manufacturing step of the BiCS memory according to the third embodiment.

FIGS. 21A and 21B are cross-sectional views showing a manufacturing step of the BiCS memory according to the third embodiment.

FIGS. 22A and 22B are cross-sectional views showing a manufacturing step of the BiCS memory according to the third embodiment.

DETAILED DESCRIPTION

In general, according to one embodiment, a nonvolatile semiconductor memory device including a semiconductor layer with a main surface, a first insulating layer formed on the main surface of the semiconductor layer, a charge storage layer formed on the first insulating layer, a second insulating layer formed on the charge storage layer, and a control gate electrode formed on the second insulating layer, wherein at least one inelastic scattering film that reduces energy of elec-

trons by scattering is contained in at least one of the charge storage layer and second insulating layer.

Embodiments will be explained in detail with reference to the accompanying drawings.

(1-1) Structure of First Embodiment

FIGS. 1A and 1B illustrate the structure of a MONOS memory cell according to a first embodiment, FIG. 1A is a cross-sectional view in a channel length direction and FIG. 1B is a cross-sectional view in a channel width direction.

On the main surface of a semiconductor layer **101**, a tunnel insulating film **102** (first insulating film), charge storage layer **103**, charge block layer **104** (second insulating layer) and control gate electrode **105** are sequentially formed in this order. In this case, the charge storage layer **103** has a lower charge storage film **103a**, inelastic scattering film **103b** and upper charge storage film **103c** sequentially formed from the bottom. The charge block layer **104** has a lower charge block film **104a**, inelastic scattering film **104b** and upper charge block film **104c** sequentially formed from the bottom. Further, regions between the respective memory cells in the channel length direction are covered with a cell-cell insulating film **107**.

As shown in FIG. 1B, element isolation insulating films **106** are formed at the sidewalls of the tunnel insulating film **102** and charge storage layer **103**.

In this case, it is defined that, for example, the trap density in the inelastic scattering film is greater than or equal to $10^{18}/\text{cm}^3$ or the difference in height of the potential barrier [barrier height] between the charge storage layer or charge block layer and the inelastic scattering film is greater than or equal to 0.2 eV. Further, it may be defined that a combination of the above two conditions is set. The "trap" means a dangling bond. That is, it is configured by a dangling bond of Si or a state in which impurities of hydrogen, boron, phosphorus, arsenic, carbon, chlorine, fluorine and metal (for example, Fe, Cr, Ni, W, Cu) are contained.

If the inelastic scattering film is defined according to the trap density in the insulating film, electrons are trapped or de-trapped in the inelastic scattering film. Therefore, energy of electrons can be taken away by temporarily trapping or de-trapping electrons leaking from the control gate electrode **105** in an erase operation.

Further, if the inelastic scattering film is defined according to the difference in barrier height, potential energy of the inelastic scattering film becomes lower than that of the surrounding insulating film. Therefore, energy of electrons leaking from the control gate electrode **105** can be taken away by so-called potential scattering at the erase operation time.

If the inelastic scattering film has charges of $10^{12}/\text{cm}^2$ or more, energy of electrons can be taken away by so-called coulomb scattering. The type of charges may be positive or negative.

FIG. 2 is a band diagram in the first embodiment. The abscissa indicates a distance from the interface of the tunnel insulating film/semiconductor layer and the ordinate indicates energy with an Si valence band set as a reference.

If an inelastic scattering film is not formed as in the prior art case, electrons leaking from the control gate electrode **105** will gain a great amount of energy until they reach the interface of the tunnel insulating film/semiconductor layer. Therefore, electrons leaking from the control gate electrode **105** are impact-ionized in the semiconductor layer **101** to generate hot holes. As a result, damage is done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer. Thus, the insulation of the tunnel insulating film **102** is degraded.

On the other hand, in this embodiment, an inelastic scattering film is formed and electrons are trapped or de-trapped in the inelastic scattering film or temporarily held as shown in FIG. 2. Thus, energy of electrons leaking from the control gate electrode **105** can be taken away. That is, since the inelastic scattering film takes away energy of electrons leaking from the control gate electrode **105** in the erase operation, electrons are not impact-ionized in the semiconductor layer **101**. Therefore, damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer can be reduced and the insulation of the tunnel insulating film **102** can be maintained. As a result, degradation of the charge holding characteristic of the MONOS memory cell can be prevented.

If damage is done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer due to electrons leaking from the control gate electrode **105**, dangling bonds will occur in this area. Therefore, electrons will be accumulated on the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer at the write/erase operation time. The electrons obstruct the write/erase operation.

In this embodiment, since damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer is reduced, the write/erase operation speed can be maintained even if the write/erase operation is repeatedly performed.

For example, the inelastic scattering film **103b** is a hafnium oxide film containing hafnium and oxygen as main components and the film thickness thereof is set to 1 to 5 nm, for example. The reason why the inelastic scattering film **103b** is formed is to reduce a larger amount of energy by trapping electrons in an energy level lower than energy of a trap level in which a silicon nitride film containing silicon and nitrogen as main components is formed.

For example, the inelastic scattering film **104b** is a silicon nitride film containing silicon and nitrogen as main components and the film thickness thereof is set to 1 to 5 nm, for example. The ratio of nitrogen to silicon in the silicon nitride film is set almost equal to the stoichiometric composition ratio (N/Si~1.33). Further, the ratio of nitrogen to silicon may be silicon-rich (N/Si<1.33) in comparison with the stoichiometric composition ratio. In this case, since the trap density in the inelastic scattering film **104b** increases, electrons tend to be trapped in the inelastic scattering film **104b**. Therefore, it becomes possible to attain the feature that energy of electrons leaking from the control gate electrode **105** is reduced in the inelastic scattering film **104b** and damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer is reduced.

Further, oxygen may be contained in the silicon nitride film. In this case, an amount of charges accumulated in the inelastic scattering film **104b** is reduced. As a result, since the possibility that electrons accumulated on the charge storage layer **103** are extracted to the control gate electrode becomes weak, the feature that the charge holding characteristic is enhanced can be attained.

Further, for example, the inelastic scattering film **104b** may be a silicon oxide film that contains silicon and oxygen as main components and further contains hydrogen, boron, phosphorus, arsenic, carbon, chlorine, fluorine or metal (for example, Fe, Cr, Ni, W). In this case, plural types of the above components may be contained.

Further, for example, the inelastic scattering film **104b** may be a hafnium oxide film containing hafnium and oxygen as main components. This is because more energy can be reduced by trapping electrons in an energy level lower than

energy of a trap level in which a silicon nitride film containing silicon and nitrogen as main components is formed.

For example, the semiconductor layer **101** contains silicon as a main component and doped with impurities. The tunnel insulating film **102** is a silicon oxide film containing silicon and oxygen as main components or a silicon oxynitride film containing silicon, oxygen and nitrogen as main components, for example, and the film thickness thereof is set to 2 to 7 nm, for example. Each of the lower charge storage film **103a** and upper charge storage film **103c** is a silicon nitride film containing silicon and nitrogen as main components, for example, and the film thickness thereof is set to 0 to 9 nm, for example.

Each of the lower charge block film **104a** and upper charge block film **104c** is an alumina film containing aluminum and oxygen as main components, a silicon oxide film containing silicon and oxygen as main components or a silicon oxynitride film containing silicon, oxygen and nitrogen as main components, for example, and the film thickness thereof is set to 8 to 20 nm, for example. Further, the lower charge block film **104a** and upper charge block film **104c** may be formed of films with different compositions.

The control gate electrode **105** may be formed of a silicon film doped with impurities, tantalum nitride or silicide of silicon and metal such as tungsten. Each of the element isolation insulating film **106** and cell-cell insulating film **107** is a silicon oxide film containing silicon and oxygen as main components.

The difference in the effect depending on a position of the charge block layer **104** in which the inelastic scattering film is formed is explained. Further, it is supposed that the film thickness of the lower charge block film **104a** is set to X nm and the film thickness of the upper charge block film **104c** is set to Y nm.

In the case of $X > Y$, the inelastic scattering film **104b** is formed in a region closer to the control gate electrode **105** rather than the charge storage layer **103**. In this case, since electrons trapped in the inelastic scattering film **104b** at the erase operation time tend to be de-trapped at the write operation time, the charge holding characteristic is enhanced.

In the case of $X < Y$, the inelastic scattering film **104b** is formed in a region closer to the charge storage layer **103** rather than the control gate electrode **105**. In this case, since a distance over which electrons extracted from the inelastic scattering film **104b** are re-accelerated becomes short at the erase operation time, an amount of energy acquired by the electrons can be suppressed. Therefore, damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer is reduced. As a result, the charge holding characteristic of the memory cell can be enhanced and the write/erase operation speed can be maintained.

In FIGS. 1A and 1B, a case wherein both of the inelastic scattering film **103b** and inelastic scattering film **104b** are formed is explained. However, in the first embodiment, only one of the inelastic scattering film **103b** and inelastic scattering film **104b** may be formed.

Further, only one of the lower charge storage film **103a** and upper charge storage film **103c** can be formed. Likewise, only one of the lower charge block film **104a** and upper charge block film **104c** can be formed. Further, each of the inelastic scattering film **103b** and inelastic scattering film **104b** may be formed to have two or more layers.

FIGS. 3A and 3B show an example in which an inelastic scattering film **104b'** is additionally formed on the upper charge block film **104c**. In this case, the feature that electrons are accumulated in the inelastic scattering film **104b'** and an

amount of electrons leaking from the control gate electrode **105** can be reduced is attained.

Further, as is explained above, energy of electrons leaking from the control gate electrode **105** is taken away by forming the inelastic scattering film **103b** or inelastic scattering film **104b**. Therefore, electrons can be suppressed from being impact-ionized in the semiconductor layer **101** and damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer can be reduced. Therefore, degradation of the insulation of the tunnel insulating film **102** can be more effectively prevented by forming the inelastic scattering film **104b'**. As a result, the charge holding characteristic of the MONOS memory cell is further enhanced.

In the first embodiment, if an inelastic scattering film of at least one layer is formed in at least one of the charge storage layer **103** and charge block layer **104**, any type of laminated structure can be formed.

(1-2) First Modification

FIG. 4A is a cross-sectional view showing a MONOS memory cell according to a modification of the first embodiment in a channel length direction and the element structure itself is the same as that of FIGS. 1A and 1B.

In the modification, the height of the barrier height of an inelastic scattering film **104b** is different on the semiconductor layer **101** side and on the control gate electrode **105** side. In this case, however, the height of the barrier height of the inelastic scattering film **104b** is changed so as to maintain the characteristic of the charge block layer **104**.

FIGS. 4B and 4C are diagrams showing the height of the barrier height of the inelastic scattering film **104b** on the Y-axis and the height of the inelastic scattering film **104b** in the channel-gate electrode direction on the X-axis.

As shown in FIG. 4B, the height of the barrier height is set larger on the semiconductor layer **101** side in comparison with the control gate electrode **105** side. In this case, since the height of the barrier height as viewed from the control gate electrode **105** becomes larger in comparison with the case of uniform height, an amount of electrons leaking from the control gate electrode **105** is suppressed. Therefore, damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer by electrons leaking from the control gate electrode **105** is reduced. As a result, the charge holding characteristic can be enhanced and the write/erase operation speed can be maintained even if the write/erase operation is repeatedly performed. The above effects can be attained in each of the cases 1 to 3 of inclinations shown in FIG. 4B.

Further, as shown in FIG. 4C, the height of the barrier height may be set larger on the control gate electrode **105** side in comparison with the semiconductor layer **101** side. In this case, since the height of the barrier height as viewed from the charge storage layer **103** becomes larger in comparison with the case of uniform height, electrons leaking from the control gate electrode **105** are accumulated in the inelastic scattering film **104b**. Therefore, damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer by electrons leaking from the control gate electrode **105** is reduced. As a result, the charge holding characteristic can be enhanced and the write/erase operation speed can be maintained even if the write/erase operation is repeatedly performed. Further, when charges are held in the charge storage layer **103**, extraction of charges from the charge storage layer **103** to the charge block layer **104** is suppressed and the charge holding characteristic is enhanced. The above effects can be attained in each of the cases 1 to 3 of inclinations shown in FIG. 4C.

When the inelastic scattering film **104b** is formed with a multi-layered laminated structure, the heights of the barrier heights of FIGS. **4B** and **4C** can be combined. In this case, since a block layer having the respective characteristics is formed, damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer is reduced.

Further, the trap density may be made different on the channel side and on the control gate electrode **105** side instead of changing the heights of the barrier heights shown in FIGS. **4B** and **4C**. For example, if the trap density is changed like the case of FIG. **4B** and when electrons trapped in the inelastic scattering film **104b** are de-trapped, the distance the electrons move between the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer becomes short. Therefore, an amount of energy acquired by the electrons is reduced. Thus, damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer is reduced. As a result, the charge holding characteristic can be enhanced and the write/erase operation speed can be maintained even if the write and erase cycle is repeated.

Further, since electrons are trapped in a region near the electrode at the erase operation time if the trap density is changed like the case of FIG. **4C**, the potential of the above region is lowered and the barrier of the charge block layer **104** as viewed from the control gate electrode **105** becomes high. Therefore, an amount of electrons injected from the control gate electrode **105** is suppressed and damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer is reduced. As a result, the charge holding characteristic can be enhanced and the write/erase operation speed can be maintained even if the write and erase cycle is repeated.

When the inelastic scattering film is formed with a multi-layered structure, the trap densities in the respective layers may be made different on the channel side and on the electrode side.

In the first modification, a case wherein the inelastic scattering film **104b** is used as an example is explained, but the same explanation can be similarly applied to the inelastic scattering film **103b**. Further, films in which the trap density or the height of the barrier height of the inelastic scattering film **104b** is changed as shown in FIG. **4B** and that of the inelastic scattering film **103b** is changed as shown in FIG. **4C** may be combined. The above relationship can be inverted.

(1-3) Second Modification

FIG. **5A** is a cross-sectional view showing a MONOS memory cell according to a modification of the first embodiment in the channel length direction and the element structure itself is the same as that of FIG. **1**.

In this modification, the height of the barrier height of the inelastic scattering film **104b** is made different along the channel length direction.

FIGS. **5B** and **5C** are diagrams showing the height of the barrier height of the inelastic scattering film **104b** on the Y-axis and the channel length of the inelastic scattering film **104b** in the channel length direction on the X-axis.

As shown in FIG. **5B**, the height of the barrier height is made larger in the end portions of the inelastic scattering film **104b** in comparison with the central portion thereof. In this case, damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer is reduced in the end portions that are difficult to be controlled by an electric field and the charge holding characteristic is enhanced in the end portions of the memory cell. Therefore, since the influence by an electric field exerts on the central

portion that is strongly controlled by an electric field even if damage is done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer, the charge holding characteristic can be maintained. Further, the write/erase operation speed can be maintained even if the write and erase cycle is repeated.

Further, as shown in FIG. **5C**, the height of the barrier height is made larger in the central portion of the inelastic scattering film **104b** in comparison with the end portions thereof. In this case, damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer is reduced in the central portion of the memory cell. Therefore, degradation of the charge holding characteristic is suppressed in the central portion of the memory cell and the write/erase speed can be maintained even if the write and erase cycle is repeated.

Further, if the charge holding characteristic in the end portion of the memory cell is degraded, an amount of charges stored in the central portion of the memory cell increases in comparison with that of the end portion. Therefore, the channel length of the memory cell can be apparently regarded as only that of the central portion in which charges are concentrated. As a result, it becomes equivalent to a case wherein the distance between the adjacent memory cells becomes larger and the feature that the effect of interference between the adjacent memory cells is suppressed can be attained.

Further, when the inelastic scattering film **104b** is formed with a multi-layered laminated structure, the heights of the barrier heights of FIGS. **5B** and **5C** can be combined. In this case, damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer is reduced on the entire surface of the memory cell. Therefore, degradation of the charge holding characteristic is suppressed and the high-speed write/erase operation can be performed even if the write and erase cycle is repeated.

Further, the trap density can be made different along the channel length direction instead of changing the height of the barrier height shown in FIGS. **5B** and **5C**. For example, if the trap density is changed like the case of FIG. **5B**, degradation of the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer is reduced in the end portion that is difficult to be controlled by an electric field and the charge holding characteristic is enhanced. Therefore, the influence by an electric field exerts on the central portion that is strongly controlled by an electric field even if damage is done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer. As a result, degradation of the charge holding characteristic is suppressed and the write/erase speed can be maintained even if the write and erase cycle is repeated.

For example, if the trap density is changed like the case of FIG. **5B**, damage done to the tunnel insulating film **102** and the interface of the tunnel insulating film/semiconductor layer is reduced in the central portion of the memory cell as in the case wherein the barrier height is similarly changed. Therefore, degradation of the charge holding characteristic in the central portion of the memory cell is suppressed and the write/erase speed can be maintained even if the write and erase cycle is repeated. Further, since this is equivalent to a case wherein the distance between the adjacent memory cells is made longer, the effect of interference between the adjacent memory cells can be suppressed.

In addition, if the inelastic scattering film is formed with a multi-layered structure, the trap densities may be made different on the channel portion and on the central portion in the respective layers.

In the second modification, a case wherein the inelastic scattering film **104b** is used as an example is explained, but the same explanation can be similarly applied to the inelastic scattering film **103b**.

Further, films in which the trap density or the height of the barrier height of the inelastic scattering film **104b** is changed as shown in FIG. 5B and that of the inelastic scattering film **103b** is changed as shown in FIG. 5C may be combined and the above relationship can be inverted.

(1-4) Third Modification

FIGS. 6A and 6B illustrate the structure of a MONOS memory cell according to a modification of the first embodiment. FIG. 6A is a cross-sectional view along the channel length direction and FIG. 6B is a cross-sectional view along the channel width direction.

First, a problem in the structure of the MONOS memory cell is explained. In the MONOS memory cell, it is necessary to form impurity regions acting as source/drain regions **108** thin to prevent occurrence of the short channel effect as the memory cell is further miniaturized. Therefore, the impurity concentration of the source/drain regions **108** becomes thin.

At the conventional erase operation time, electrons leaking from the control gate electrode **105** pass through the cell-cell insulating film **107**, give damage to the cell-cell insulating film **107** near the interface of the source/drain regions **108** and cell-cell insulating film **107** and cause dangling bonds to occur. If electrons are accumulated in the dangling bonds, they repel electrons stored in the source/drain regions **108** to form a depletion layer in the source/drain regions **108**. As a result, there occurs a problem that the resistance of the source/drain regions **108** increases.

Therefore, in the modification of the first embodiment, an inelastic scattering film **109** having the same structure as the inelastic scattering film **103b** or inelastic scattering film **104b** is formed in the cell-cell insulating film **107**.

As shown in FIGS. 6A and 6B, an increase in energy of electrons leaking from the control gate electrode **105** to the source/drain regions **108** via the cell-cell insulating film **107** can be suppressed by providing an inelastic scattering film. In this case, damage given to the cell-cell insulating film **107** near the interface of the source/drain regions and cell-cell insulating film is reduced. Therefore, since a portion near the interface of the source/drain regions and cell-cell insulating film can be suppressed from being depleted, an increase in the resistance can be suppressed. As a result, the write/erase speed can be maintained even if the write and erase cycle is repeated.

In FIGS. 6A and 6B, a case wherein the inelastic scattering film **109** is formed in the cell-cell insulating film **107** between the inelastic scattering films **104b** is explained. However, the inelastic scattering film **109** may be formed in the cell-cell insulating film **107** between the inelastic scattering films **103b**. Further, the inelastic scattering films **109** may be formed between the inelastic scattering films **103b** and between the inelastic scattering films **104b**, respectively. Like the above case, in these cases, damage given to the cell-cell insulating film **107** near the interface of the source/drain regions and cell-cell insulating film is reduced.

(1-5) Manufacturing Method of First Embodiment

Next, the manufacturing method of the MONOS memory cell transistor in the first embodiment is explained with reference to FIGS. 7A and 7B to FIGS. 10A and 10B.

FIG. 7A to FIG. 10A are cross-sectional views along the channel length direction and FIG. 7B to FIG. 10B are cross-sectional views along the channel width direction.

First, as shown in FIGS. 7A and 7B, for example, the surface of a semiconductor layer **101** in which impurities are

doped to a desired concentration is exposed to an oxygen atmosphere of 800° C., for example, to form a tunnel insulating film **102** with a thickness of 5 nm formed of a silicon oxide film. Then, a lower charge storage film **103a** with a thickness of 2 nm formed of a silicon nitride film is deposited by use of the chemical vapor deposition (CVD) method, for example. After this, an inelastic scattering film **103b** with a thickness of 1 nm formed of a hafnium oxide film is deposited by use of a reactive sputtering method of argon and oxygen, for example. Next, an upper charge storage film **103c** with a thickness of 2 nm formed of a silicon nitride film is deposited by use of the CVD method, for example, to form a charge storage layer **103**. Then, a processing mask member **111** is deposited by use of the CVD method, for example.

Next, as shown in FIGS. 8A and 8B, for example, the processing mask member **111**, charge storage layer **103** and tunnel insulating film **102** are sequentially etched by use of an RIE method using a resist mask to expose the semiconductor layer **101**. Further, the exposed portion of the semiconductor layer **101** is etched to the depth of approximately 100 nm to form element isolation grooves **112**.

Next, as shown in FIGS. 9A and 9B, for example, element isolation insulating films **112b** formed of a silicon oxide film are formed by using a combination of a coating method and the chemical mechanical polishing (CMP) method. Then, the processing mask member **111** is removed and a lower charge block film **104a** with a thickness of 7 nm formed of an alumina film is deposited by use of the atomic layer deposition (ALD) method, for example. Subsequently, an inelastic scattering film **104b** with a thickness of 3 nm formed of a silicon nitride film is deposited by use of the CVD method, for example. Then, an upper charge block film **104c** with a thickness of 4 nm formed of an alumina film is deposited by use of the ALD method, for example, to form a charge block layer **104**. After this, a control gate electrode **105** and processing mask member **113** formed of a polysilicon film doped with impurities and having a thickness of 200 nm, for example, are deposited by use of the CVD method, for example.

Next, as shown in FIGS. 10A and 10B, for example, the processing mask member **113**, control gate electrode **105**, charge block layer **104** and charge storage layer **103** are sequentially etched and processed by use of the RIE method using a resist mask, for example, to form control gate electrodes **105** that cause the distance between the adjacent memory cells to be set to 30 nm, for example, and cause the channel length thereof to be set to 30 nm, for example. At this time, the structure is formed to expose the surface of the tunnel insulating film **102**. Further, source/drain regions **108** may be formed near the upper surface of the semiconductor layer **101** as required by use of an ion-implantation method, for example.

Next, the processing mask member **113** is removed and a cell-cell insulating film **107** formed of a silicon oxide film is formed by using, for example, a combination of a coating method and CMP method. Then, interconnection layers and the like are formed by use of a known technique to complete the MONOS memory cell transistor shown in FIGS. 1A and 1B.

Next, the manufacturing method in the first modification of the first embodiment is explained.

First, a case wherein the barrier height of the inelastic scattering film **104b** varies in a direction from the channel towards the control gate electrode **105** as shown in FIG. 4A is explained.

After the lower charge block film **104a** is formed as shown in FIGS. 9A and 9B, a silicon film of one-atom layer is formed by using Si source gas of SiH₂Cl₂, for example, by use of the

ALD method. Next, active oxygen such as an O_2 radical, O_3 is supplied at a flow rate x to oxidize a silicon film. Then, nitrogen-series gas such as an NH radical, NH_3 is supplied at a flow rate y to nitride the silicon oxide film. As a result, a silicon oxynitride film is formed. At this time, it is supposed that the film formation temperature is set to 700° C. or less. Then, a silicon layer of one-atom layer is formed on the oxynitride film like the above case and the flow rates x and y are adequately changed to form an oxynitride film in which the nitrogen concentration and oxygen concentration are changed.

Thus, an oxynitride film having desired nitrogen concentration distribution and oxygen concentration distribution can be formed by depositing an oxynitride film whose concentration is changed until desired film thickness is attained. Therefore, the barrier height of the inelastic scattering film **104b** can be made different in a direction from the semiconductor layer **101** towards the control gate electrode **105**.

Further, an inelastic scattering film **104b** is formed as shown in FIGS. 9A and 9B as another method for making the barrier height of the inelastic scattering film **104b** lower in a direction from the semiconductor layer **101** towards the control gate electrode **105** as shown in FIG. 4B. Then, the barrier height shown in FIG. 4B is attained by exposing the structure to an oxygen atmosphere of 800° C., for example, and oxidizing a portion thereof on the surface side.

Next, a case wherein the trap density of the inelastic scattering film **104b** varies in a direction from the semiconductor layer **101** towards the control gate electrode **105** is explained.

As shown in FIGS. 9A and 9B, a silicon oxide film is formed by use of the CVD method using disilane, oxygen and diborane after the lower charge block film **104a** was formed. At this time, if the flow rates of oxygen and diborane are respectively set to x and y , the ratio of the flow rate x of oxygen to the flow rate y of diborane is changed in the initial stage of film formation and in the later stage. Therefore, the trap density of the inelastic scattering film **104b** can be made different in a direction from the semiconductor layer **101** towards the control gate electrode **105**.

Next, the manufacturing method in the second modification of the first embodiment is explained.

First, as shown in FIG. 5B, a case wherein the barrier height is set low in the end portions of the inelastic scattering film **104b** is explained. In FIGS. 10A and 10B, nitrogen can be introduced into the end portions of the inelastic scattering film **104b** by processing the structure in a nitrogen radical atmosphere after the processing mask member **113**, control gate electrode **105**, charge block layer **104** and charge storage layer **103** are sequentially etched by use of the RIE method using a resist mask. Therefore, the barrier height can be made low in the end portions of the inelastic scattering film **104b**.

Further, as shown in FIG. 5C, in a case where the barrier height is set high in the end portions of the inelastic scattering film **104b**, oxygen can be introduced into the end portions of the inelastic scattering film **104b** by processing the structure in an oxygen radical atmosphere or oxygen atmosphere of 700° C. or more instead of processing the structure in the nitrogen radical atmosphere. Therefore, the barrier height can be made high in the end portions of the inelastic scattering film **104b**.

Next, a case wherein the trap density is set low in the end portions of the inelastic scattering film **104b** is explained. An inelastic scattering film **104b** is formed by use of the CVD method using disilane and oxygen and a cell-cell insulating film **107** is formed by use of a combination of the CMP method and coating method using oxygen and diborane. Then, for example, the heat treatment is performed at 700 to

950° C. to laterally diffuse boron from the cell-cell insulating film **107** to the inelastic scattering film **104b**. Therefore, the trap density can be made lower in the end portions of the inelastic scattering film **104b** than in the central portion thereof by supplying a larger amount of boron to the end portions than the central portion of the inelastic scattering film **104b**.

Next, a case wherein the trap density is set high in the end portions of the inelastic scattering film **104b** is explained. An inelastic scattering film **104b** is formed by use of the CVD method using disilane, oxygen and diborane and a cell-cell insulating film **107** is formed by use of a combination of the CMP method and coating method using disilane and oxygen. Then, for example, the heat treatment is performed at 700 to 950° C. to laterally diffuse boron from the inelastic scattering film **104b** to the cell-cell insulating film **107**. Therefore, the trap density can be made higher in the end portions of the inelastic scattering film **104b** than in the central portion thereof since boron in the end portions of the inelastic scattering film **104b** is diffused into the cell-cell insulating film.

Next, the manufacturing method in the third modification of the first embodiment is explained.

In FIGS. 9A and 9B, an inelastic scattering film **104b** formed of a silicon nitride film is formed by use of the CVD method using disilane, oxygen and diborane. Then, like the manufacturing method of the first embodiment, an upper charge block film **104c**, control gate electrode **105** and the like are formed. Next, in FIGS. 6A and 6B, a cell-cell insulating film **107** formed of a silicon oxide film is formed by use of a combination of the CMP method and coating method using disilane and oxygen. After the cell-cell insulating film **107** is formed, for example, the heat treatment is performed at 700 to 950° C. to diffuse boron from the inelastic scattering film **104b** to the cell-cell insulating film **107**. As a result, an inelastic scattering film **109** is formed in the cell-cell insulating film.

(2-1) Structure of Second Embodiment

FIGS. 11A and 11B illustrate the structure of a depletion MONOS memory cell to which the silicon-on-insulator (SOI) technique is applied, FIG. 11A is a cross-sectional view in the channel length direction and FIG. 11B is a cross-sectional view in the channel width direction.

In the depletion MONOS memory cell of the second embodiment, it is supposed that the distance between adjacent memory cells is set to 100 nm or less and the channel width of the memory cell is also set to 100 nm or less.

An insulating layer **200a** is formed on the upper surface of a silicon substrate **200** and semiconductor layers **201** are formed on the upper surface of the insulating layer **200a**. Further, tunnel insulating films **202** (first insulating layer), charge storage layers **203**, charge block layer **204** (second insulating layer) and control gate electrodes **205** are sequentially formed in this order on the surface of the semiconductor layer **201**. In this case, the charge storage layer **203** includes a lower charge storage film **203a**, inelastic scattering film **203b** and upper charge storage film **203c** formed sequentially from the bottom and the charge block layer **204** includes a lower charge block film **204a**, inelastic scattering film **204b** and upper charge block film **204c** formed sequentially from the bottom. Further, the control gate electrodes **205** in the channel length direction are covered with a cell-cell insulating film **207** and separated as memory cells.

As shown in FIG. 11B, element isolation insulating films **206** are filled in space areas between the sidewalls of the tunnel insulating films **202** and charge storage layers **203** to isolate the memory cells in the channel width direction.

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In this case, the inelastic scattering film is similarly defined as in the first embodiment and the detailed explanation thereof is omitted.

In the second embodiment, the inelastic scattering film **203b** is formed in the charge storage layer **203** and the inelastic scattering film **204b** is formed in the charge block layer **204**. Since the above inelastic scattering films take energy of electrons leaking from the control gate electrodes **205** in the erase operation, electrons are not impact-ionized in the semiconductor layers **201**. Therefore, damage done to the tunnel insulating film **202** and the interface of the tunnel insulating film/semiconductor layer is reduced and thus the insulation of the tunnel insulating film **202** can be maintained. As a result, the charge holding characteristic of the depletion MONOS memory cell can be prevented from being degraded.

Like the first embodiment, in the second embodiment, since damage done to the tunnel insulating film **202** and the interface of the tunnel insulating film/semiconductor layer is reduced, the write/erase speed can be maintained even if the write/erase operation is repeatedly performed.

Further, since the constituent materials, the condition of film thickness and the formation condition of the respective films of the depletion MONOS memory cell are the same as the constituent materials, the condition of film thickness and the formation condition of the respective films in the first embodiment, the detailed explanation thereof is omitted. For example, the insulating layer **200a** is formed of a silicon oxide film containing silicon and oxygen as main components.

(2-2) First Modification

FIG. **12A** is a cross-sectional view showing a depletion MONOS memory cell according to a modification of the second embodiment in the channel length direction and the element structure itself is the same as that of FIGS. **11A** and **11B**.

FIG. **12B** is a diagram showing the trap density of the inelastic scattering film **204b** on the Y-axis and the channel length of the inelastic scattering film **204b** in the channel length direction on the X-axis.

In the depletion MONOS memory cell, an electric field applied to the channel region between the memory cells is weaker than an electric field applied to the channel region under the memory cell. Therefore, if electrons leaking from the control gate electrode **205** break down the tunnel insulating film **202** formed between the memory cells and the tunnel insulating film **202** formed near the interface of the tunnel insulating film/semiconductor layer at the erase operation time, the resistance of the semiconductor layer **201** between the memory cells increases. As a result, there occurs a problem that the device does not function as a depletion memory cell.

Therefore, in the modification of the second embodiment, the trap density of the inelastic scattering film is varied in the channel length direction. Specifically, the trap density of the inelastic scattering film **204b** formed between the memory cells is made higher than the trap density of the inelastic scattering film **204b** formed in the lower portion of the memory cell.

In this case, when electrons leaking from the control gate electrode **205** pass through the inelastic scattering film **204b** between the memory cells at the erase operation time, the electrons tend to be trapped in the inelastic scattering film **204b**. Therefore, the tunnel insulating film **202** and the tunnel insulating film **202** formed near the interface of the tunnel insulating film/semiconductor layer can be prevented from being broken down and an increase in the resistance of the

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semiconductor layer **201** can be suppressed. As a result, the write/erase speed can be maintained.

(2-2) Manufacturing Method

Next, the manufacturing method of the depletion MONOS memory cell in the second embodiment is explained with reference to FIGS. **13A** and **13B** to FIGS. **17A** and **17B**. FIG. **13A** to FIG. **17A** are cross-sectional views showing the depletion MONOS memory cell in the channel length direction and FIG. **13B** to FIG. **17B** are cross-sectional views showing the depletion MONOS memory cell in the channel width direction.

First, as shown in FIGS. **13A** and **13B**, the surface of a semiconductor layer **201** on an SOI substrate having desired impurities doped therein is exposed to an oxygen atmosphere of 800° C., for example, to form a tunnel insulating film **202** with a thickness of 5 nm formed of a silicon oxide film. Further, a lower charge storage film **203a** with a thickness of 2 nm formed of a silicon nitride film is deposited by the CVD method, for example. Then, an inelastic scattering film **203b** with a thickness of 1 nm formed of a hafnium oxide film is deposited by use of a reactive sputtering method of argon and oxygen, for example. Next, an upper charge storage film **203c** with a thickness of 2 nm formed of a silicon nitride film is deposited by use of the CVD method, for example, to form a charge storage layer **203**. Then, a processing mask member **211** is deposited by use of the CVD method, for example.

Next, as shown in FIGS. **14A** and **14B**, the processing mask member **211**, charge storage layer **203** and tunnel insulating film **202** are sequentially etched by use of, for example, the RIE method using a resist mask to expose the semiconductor layer **201**. Further, the exposed portion of the semiconductor layer **201** is etched to the depth of approximately 100 nm to form element isolation grooves **212**.

Next, as shown in FIGS. **15A** and **15B**, element isolation insulating films **212b** formed of a silicon oxide film are formed by using, for example, a combination of a coating method and the chemical mechanical polishing (CMP) method. Then, the processing mask member **211** is removed and a lower charge block film **204a** with a thickness of 7 nm formed of an alumina film is deposited by use of the atomic layer deposition (ALD) method, for example. Subsequently, an inelastic scattering film **204b** with a thickness of 3 nm formed of a silicon nitride film is deposited by use of the CVD method, for example. Then, an upper charge block film **204c** with a thickness of 4 nm formed of an alumina film is deposited by use of the ALD method, for example, to form a charge block layer **204**. After this, a control gate electrode **205** and processing mask member **213** formed of a polysilicon film doped with impurities and having a thickness of 200 nm, for example, are deposited by use of the CVD method, for example.

Next, as shown in FIGS. **16A** and **16B**, the processing mask member **213** and control gate electrode **105** are sequentially etched by use of, for example, the RIE method using a resist mask to form control gate electrodes **205** that cause the distance between the adjacent memory cells to be set to 30 nm, for example, and cause the channel length thereof to be set to 30 nm, for example.

Next, as shown in FIGS. **17A** and **17B**, after the processing mask member **213** is removed, a cell-cell insulating film **207** formed of a silicon oxide film is formed by using, for example, a combination of a coating method and CMP method. Then, interconnection layers and the like are formed by use of a known technique to complete the depletion MONOS memory cell transistor according to the second embodiment.

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Next, the manufacturing method in a modification of the second embodiment is explained.

First, as shown in FIGS. 17A and 17B, a cell-cell insulating film 207 is formed by use of the CVD method using disilane, oxygen and diborane after the control gate electrode 205 was formed and the processing mask member was removed. Then, the heat treatment is performed at 700 to 950° C. to diffuse boron from the cell-cell insulating film 207 towards the charge block layer 204 that faces the cell-cell insulating film 207. As a result, since the trap density of the inelastic scattering film 204b formed below the cell-cell insulating film can be increased, the inelastic scattering film 204b formed between the memory cells can be formed to have desired trap density as shown in FIG. 12B. Further, the inelastic scattering film 204b may be formed of a material other than the silicon nitride film or a material equivalent to that of the lower charge block film 204a and upper charge block film 204c.

(3-1) Structure of Third Embodiment

Next, a third embodiment is explained with reference to the accompanying drawings by taking a memory (hereinafter referred to as a bit-cost scalable [BiCS] memory) to which the BiCS technique is applied as an example.

FIGS. 18A and 18B illustrate the structure of one memory cell of a BiCS memory according to a third embodiment, FIG. 18A is a bird's-eye view and FIG. 18B is a cross-sectional view taken along line A-A of FIG. 18A. In this case, it is supposed that the distance between the adjacent memory cells is set to approximately 50 nm, for example.

A tunnel insulating film (third insulating layer) 302, charge storage layer 303 formed of an insulating film and charge block layer (second insulating layer) 304 are sequentially formed on the peripheral portion of a column-shaped semiconductor layer 301 vertically formed on a semiconductor layer. In this case, the charge storage layer 303 has an inner charge storage film 303a, inelastic scattering film 303b and outer charge storage film 303c formed sequentially from a portion near the semiconductor layer 301. The charge block layer 304 has an inner charge block film 304a, inelastic scattering film 304b and outer charge block film 304c formed sequentially from a portion near the semiconductor layer 301. Further, control gate electrodes 305 laminated in a direction perpendicular to the substrate surface and isolated by cell-cell insulating films (first insulating layers) 306 are formed on the outer peripheral portion of the charge block layer 304.

In the bird's-eye view of FIG. 18A, only one layer of the control gate electrode 305 and cell-cell insulating film 306 is shown, but in practice, the control gate electrodes 305 and cell-cell insulating films 306 have a multi-layered laminated structure as shown in FIG. 18B and may be formed of a desired number of layers. Thus, memory cells arranged side by side to cover the semiconductor layer 301 configure a NAND string.

In this case, the inelastic scattering film is similarly defined as in the first embodiment and the detailed explanation thereof is omitted.

In the third embodiment, the inelastic scattering film 303b is formed in the charge storage layer 303 and the inelastic scattering film 304b is formed in the charge block layer 304. Since the above inelastic scattering films take energy of electrons leaking from the control gate electrodes 305 in the erase operation, electrons are not impact-ionized in the semiconductor layers 301. Therefore, damage done to the tunnel insulating film 302 and the interface of the tunnel insulating film/semiconductor layer is reduced and thus the insulation of the tunnel insulating film 302 can be maintained. As a result, the charge holding characteristic of the BiCS memory cell can be prevented from being degraded.

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Like the first and second embodiments, in the third embodiment, since damage done to the tunnel insulating film 302 and the interface of the tunnel insulating film/semiconductor layer is reduced, the write/erase speed can be maintained even if the write/erase operation is repeatedly performed.

Further, since the constituent materials of the respective films of the memory cell, the condition of film thickness of the respective films other than the inelastic scattering films and the formation condition are the same as the constituent materials, the condition of film thickness and the formation condition of the films in the first embodiment, the detailed explanation thereof is omitted.

In the BiCS memory, as shown in FIG. 18B, the radius of the semiconductor layer 301 is made small in the lower portion (on the semiconductor substrate side) of the semiconductor layer 301 and is made large in the upper portion (on the bit line side) of the semiconductor layer 301. Therefore, since an electric field applied to the charge block layer 304 formed on the lower portion of the semiconductor layer 301 becomes weak, the number of electrons leaking from the control gate electrode 305 becomes smaller and an amount of energy acquired by the leak electrons until they reach the interface of the tunnel insulating film/semiconductor layer becomes small. Therefore, damage done to the tunnel insulating film 302 and the interface of the tunnel insulating film/semiconductor layer is less. Further, since an electric field applied to the charge block layer 304 formed on the upper portion of the semiconductor layer 301 becomes strong, the number of electrons leaking from the control gate electrode 305 becomes larger and an amount of energy acquired by the leak electrons until they reach the interface of the tunnel insulating film/semiconductor layer becomes large. Therefore, damage done to the tunnel insulating film 302 and the interface of the tunnel insulating film/semiconductor layer is greater. As a result, since damage done to the tunnel insulating film 302 and the interface of the tunnel insulating film/semiconductor layer formed on the upper and lower portions of the semiconductor layer 301 varies, there occurs a problem that the charge holding characteristic will vary when the write/erase operation is repeatedly performed.

In the third embodiment, the inelastic scattering film 303b and inelastic scattering film 304b are formed thin on the lower portion of the semiconductor layer 301 and formed thick on the upper portion thereof. At this time, it is supposed that the difference in the film thickness on the upper and lower portions of the inelastic scattering film 304b is set to approximately 1 to 7 nm, for example. As a result, the intensity of an electric field applied to the charge block layer 304 formed on the upper portion of the semiconductor layer 301 is reduced and a variation in the intensity of an electric field applied to the charge block layer 304 formed on the upper and lower portions of the semiconductor layer 301 becomes less. This is because the difference between the radius of the control gate electrode 305 and the radius of the semiconductor layer 301 becomes smaller in the upper and lower portions of the semiconductor layer 301. Further, as is explained in the first embodiment, more energy can be taken away from electrons as the film thickness of the inelastic scattering film becomes larger or the trap density becomes higher. Therefore, damage done to the tunnel insulating film 302 and the interface of the tunnel insulating film/semiconductor layer can be reduced by forming the inelastic scattering film thick on the upper portion of the semiconductor layer 301.

Therefore, in the third embodiment, the intensity of an electric field applied to the charge block layer 304 formed on the upper portion of the semiconductor layer 301 can be made

weak, the number of electrons leaking from the control gate electrode **305** can be reduced and damage done to the tunnel insulating film **302** and the interface of the tunnel insulating film/semiconductor layer can be reduced. As a result, the charge holding characteristic of the BiCS memory can be prevented from being degraded. Therefore, the feature that the charge holding characteristic can be maintained even if the write/erase operation is repeatedly performed is attained.

(3-2) Manufacturing Method of Third Embodiment

Next, the manufacturing method of the BiCS memory according to the third embodiment is explained with reference to FIGS. **19A** and **19B** to FIGS. **22A** and **22B**. FIG. **19A** to FIG. **22A** are cross-sectional views taken along line A-A of FIG. **18A**, and FIG. **19B** to FIG. **22B** are plan views of the BiCS memory.

First, as shown in FIGS. **19A** and **19B**, cell-cell insulating films (first insulating films) **306** each formed of a silicon oxide film with a thickness of 50 nm and control gate electrodes **305** each formed of a silicon film doped with impurities with a thickness of 50 nm are alternately deposited to form a multi-layered laminated structure by use of the CVD method, for example, on the surface of a semiconductor layer **300**. In FIGS. **19A** and **19B**, a case wherein the laminated structure is a two-layered structure is shown, but the structure may be formed of a desired number of layers. Further, it is supposed that source diffusion layers and source line-side select gate lines are formed in the semiconductor layer **300**.

Next, as shown in FIGS. **20A** and **20B**, the cell-cell insulating films **306** and control gate electrodes **305** are selectively etched by use of the RIE method using a resist mask (not shown) until the surface of the semiconductor layer **300** is exposed. Thus, a column-shaped groove **311** with a diameter of approximately 70 nm, for example, is formed in the multi-layered laminated structure. When the cell-cell insulating films **306** and control gate electrodes **305** are selectively etched and removed, the column-shaped groove is formed in a forward-tapered shape with the groove diameter set small on the semiconductor layer side and the groove diameter set large on the surface side thereof.

Next, as shown in FIGS. **21A** and **21B**, an outer charge block film **304c** formed of a silicon oxide film with a thickness of 3 nm is deposited on the inner wall of the column-shaped groove **311** by use of the ALD method, for example. Then, an inelastic scattering film **304b** formed of a silicon nitride film with a thickness of 3 nm is formed by use of the CVD method. Subsequently, an inner charge block film **304a** formed of a silicon oxide film with a thickness of 7 nm is deposited by use of the ALD method to form a charge block layer (second insulating layer) **304**. After this, an outer charge storage film **303c** formed of a silicon nitride film with a thickness of 2 nm is deposited by use of the ALD method, for example. Then, an inelastic scattering film **303b** formed of a hafnium oxide film with a thickness of 1 nm is deposited by use of the reactive sputtering method using argon and oxygen. Subsequently, an inner charge storage film **303a** formed of a silicon nitride film with a thickness of 2 nm is deposited by use of the ALD method to form a charge storage layer **303**. After this, a tunnel insulating film (third insulating layer) **302** formed of a silicon oxide film with a thickness of 5 nm is formed by use of the ALD method, for example.

Next, as shown in FIGS. **22A** and **22B**, portions of the tunnel insulating film **302**, charge storage layer **303** and charge block layer **304** formed on the bottom surface portion of the column-shaped groove **311** are selectively etched by use of the RIE method using a resist mask to expose the surface of the semiconductor layer **300**. Then, after a semiconductor layer **301** having impurities doped therein and used

as a channel region is deposited by use of the CVD method, for example, the heat treatment is performed in a nitrogen atmosphere of 600° C. After this, interconnection layers and the like are formed by use of a known technique to complete a BiCS memory.

When the inelastic scattering film **304b** is formed thicker in a higher portion of the semiconductor layer **301**, the following method may be used. For example, a nitride film can be formed thicker in a portion closer to the surface side of the column-shaped groove **311** and formed thinner in a portion of the column-shaped groove **311** closer to the semiconductor layer **300** by simultaneously supplying dichlorosilane (SiCl₂H₂) and NH₃ gas and forming the film at the film formation temperature of approximately 650 to 800° C. in a pressure condition of approximately 0.3 to 10 Torr by use of the CVD method, for example. Further, the film can be similarly formed by use of the PECVD method. In this case, the difference in the film thickness in the upper portion and lower portion of the inelastic scattering film **304b** is approximately 1 to 7 nm.

(4) Modification of Present Invention

The present invention is not limited to the above embodiments and can be embodied by modifying the constituents without departing from the scope. Further, various inventions can be made by adequately combining a plurality of constituents disclosed in the above embodiments. For example, some constituents may be removed from all of the constituents disclosed in the above embodiments or constituents disclosed in the different embodiments may be adequately combined. In addition, the memory structure of this invention may be applied to both of the NAND memory cells and NOR memory cells.

While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions. Indeed, the novel embodiments described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the embodiments described herein may be made without departing from the spirit of the inventions. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the inventions.

What is claimed is:

1. A nonvolatile semiconductor memory device, comprising:
 - a base insulating layer;
 - semiconductor layers buried in the base insulating layer and which are column-shaped, each of the semiconductor layers extending in a first direction, the semiconductor layers having a first semiconductor layer, a second semiconductor layer and a third semiconductor layer, the first semiconductor layer and the second semiconductor layer arranged spaced apart with a first part of the base insulating layer interposed therebetween along a second direction perpendicular to the first direction, the first semiconductor layer and the third semiconductor layer arranged spaced apart with a second part of the base insulating layer interposed therebetween along a third direction perpendicular to the first direction and the second direction;
 - conductive layers arranged along the first direction, the conductive layers having a first conductive layer;
 - a charge storage layer disposed between the first semiconductor layer and the first conductive layer;
 - a first insulating layer disposed between the first semiconductor layer and the charge storage layer;

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a second insulating layer disposed between the first conductive layer and the charge storage layer, the second insulating layer having an insulating film containing hafnium and oxygen.

2. The device according to claim 1, wherein trap density of the insulating film of the second insulating layer is not less than $10^{18}/\text{cm}^3$.

3. The device according to claim 1, wherein a potential barrier of the insulating film of the second insulating layer on the first conductive layer side is different from that of the semiconductor layers side.

4. The device according to claim 1, wherein a potential barrier of the insulating film of the second insulating layer is different between a central portion and an end portion in a channel length direction defined by the first conductive layer.

5. The device according to claim 1, wherein trap density of the insulating film of the second insulating layer on the first conductive layer side is different from that of the semiconductor layers side.

6. The device according to claim 1, further comprising a plurality of memory devices, each being the device, wherein the insulating film is continuously formed between adjacent ones of the memory devices.

7. A nonvolatile semiconductor memory device, comprising:

a base insulating layer;

semiconductor layers buried in the base insulating layer and column-shaped, each of the semiconductor layers extending in a first direction, the semiconductor layers having a first semiconductor layer, a second semiconductor layer and a third semiconductor layer, the first semiconductor layer and the second semiconductor layer arranged as being spaced apart with a first part of the base insulating layer interposed therebetween along a second direction perpendicular to the first direction,

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the first semiconductor layer and the third semiconductor layer arranged as being spaced apart with a second part of the base insulating layer interposed therebetween a third direction perpendicular to the first direction and the second direction;

conductive layers arranged along the first direction, the conductive layers having a first conductive layer;

a charge storage layer disposed between the first semiconductor layer and the first conductive layer, and having a laminated structure of a charge storage film and a hafnium oxide film containing hafnium and oxygen;

a first insulating layer disposed between the first semiconductor layer and the charge storage layer;

a second insulating layer disposed between the first conductive layer and the charge storage layer.

8. The device according to claim 7, wherein trap density of the insulating film of the second insulating layer is not less than $10^{18}/\text{cm}^3$.

9. The device according to claim 7, wherein a potential barrier of the insulating film of the second insulating layer on the first conductive layer side is different from that of the semiconductor layers side.

10. The device according to claim 7, wherein a potential barrier of the insulating film of the second insulating layer is different between a central portion and an end portion in a channel length direction defined by the first conductive layer.

11. The device according to claim 7, wherein trap density of the insulating film of the second insulating layer on the first conductive layer side is different from that of the semiconductor layers side.

12. The device according to claim 7, further comprising a plurality of memory devices, each being the device, wherein the insulating film is continuously formed between adjacent ones of the memory devices.

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